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A DICTIONARY

OF

APPLIED PHYSICS

EDITED BY

SIR RICHARD GLAZEBROOK

K.C.B., D.Sc., F.R.S.

IN FIVE VOLUMES

VOL. V

AERONAUTICS—METALLURGY

GENERAL INDEX

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AERODYNAMIC RESEARCH, FULL SCALE

AN ACCOUNT OF THE METHODS AND APPARATUS EMPLOYED AT THE ROYAL AIRCRAFT ESTABLISHMENT

§ (1) INTRODUCTORY.—Research work in aeronautics may be classified under the two heads of work in the laboratory and work in the air. On the aerodynamic side, the laboratory work consists almost entirely of tests of models in a wind tunnel. The wind tunnel plays in aeronautics much the same part as the Froude tank plays in marine engineering. Apart from the widely different state of development of the two branches of engineering, there is, however, this important difference. In the case of a body moving in the free surface of a liquid, acted on by gravity, the law [1] of Dynamic Similarity requires that the model should be tested at a speed directly proportional to the square root of the scale of its linear dimensions; but in the case of a body moving through the atmosphere the model must be tested at a speed inversely proportional to the scale. It is possible to satisfy the conditions for dynamic similarity in the tank; but the speed required for this in a wind tunnel is not practicable. A tunnel of prohibitive dimensions would be required, as for a small model the speed would be so great that the compressibility of the air would become important and the results would be vitiated on this account. The value of wind-tunnel results depends, therefore, to an appreciable extent on the accuracy with which the relation between model and full scale is known.

At the same time it should be remembered that the forces with which the investigation is concerned vary approximately as the square of the speed and the square of the linear dimensions.

The scale effect introduces a correction to this, often of great importance, but valuable information can be obtained in some cases from model experiments without an exact knowledge of the correction. The value of the possibility of using wind tunnels in aeronautical research is so great that full-scale work should largely be devoted to obtaining the closest possible comparisons with model measurements. It is not necessary to enlarge upon the possible saving of time, money, and life involved, and the wind tunnel is obviously more readily adaptable to analytical measurement. There remain, however, cases — for instance, when the handling of an aeroplane by different pilots is concerned—where only full-scale observation is of value.

Some of the methods employed for full-scale research to be described are practically identical with the methods of measurement employed for routine testing of aeroplane performance, in particular the methods of measuring speed, rate of climb, and longitudinal stability. An attempt will be made to describe briefly the general principles of

[1] See "Dynamical Similarity," § (1), Vol. I.; also "Aircraft Model Experiments."

the methods and apparatus employed for measuring the speed, rate of climb, and lowest flying speed, and determining the lift and the drag of an aeroplane and the thrust of the airscrew; of determining the possible loads occurring on the structure in flight and the distribution of the load; of investigating stability, manœuvrability, and control.

§ (2) Aeroplane Performance.—The word "performance" is commonly used to denote the speed at which an aeroplane can fly level, and the rate at which it can climb at various heights above sea-level. The forces exerted by the air upon a body moving through it depend upon the density of the air and upon the velocity of motion. The density is thus one of the quantities requiring measurement, and is obtained by observations of atmospheric pressure and temperature. As the performance of the engine may depend upon both the density and the temperature of the atmosphere, temperature observations are in any case required in addition to the measurement of density, wherever the engine is involved. The pressure is obtained by means of an aneroid barometer, which is carried in all aeroplanes as an indicator of height. The principle of operation of this instrument is so familiar that it need not be described here. The aeroplane aneroid differs from the domestic aneroid chiefly in having a larger range and a less open scale, which is graduated in feet of height above sea-level in an arbitrary atmosphere of uniform temperature (10° C.). The aneroid is designed with a view to reducing lag in operation to a minimum, and the best instruments used on research work are very good in this respect. It is also carefully compensated for effects of temperature variations upon its indications as a pressure gauge. For experimental purposes aeroplanes are fitted with a special alcohol thermometer in an exposed position, having a bulb of large surface/volume ratio, so that it shall quickly follow changes of temperature. The aneroid serves the double purpose, from the experimental point of view, of determining the atmospheric pressure and measuring the rate of climb in conjunction with a stop-watch. For the latter purpose the observations require correction for variation of the atmospheric temperature from the arbitrary constant temperature for which the aneroid is calibrated.

The speed of flight is measured by means of the "air-speed indicator," which forms a standard part of the instrumental equipment of all British aeroplanes.

§ (3) The Air-speed Indicator.—Perhaps the most obvious method of determining the speed of the aeroplane through the air is by measuring the rate of revolution of an anemometer, consisting of a small screw-shaped windmill, a method commonly employed upon German aeroplanes. This form of instrument has been used in this country for meteorological purposes and for measuring air flow in mines, etc., and is now being developed as an air-log for aerial navigation. The instrument used on British aeroplanes

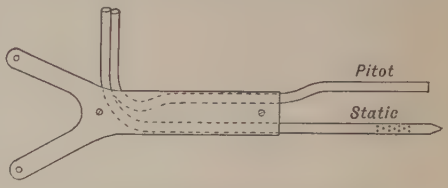

Fig. 1.—Pitot and Static Tubes, as fitted to an Aeroplane.

does not directly determine the true air speed, but measures pressure due to the motion, and so involves the density of the air. For ordinary flying purposes and for experimental work this is really more useful than a true indication of speed, as it measures directly the quantity upon which the reaction of a body moving through the air at a definite attitude depends. Given the weight and aerodynamic properties of the aeroplane, this "indicated speed" is in steady flight a measure of the attitude at which the aeroplane is meeting the air. In this instrument (*Fig.* 1) opposite sides of a sensitive pressure gauge are connected to a "Pitot" tube and to a "static" tube. The Pitot is an open-ended tube pointing up-wind. The static tube has a pointed end facing up-wind and a number of small holes drilled through its walls a short distance back from the "streamline" point. As the flow past these holes is parallel flow, the pressure in the tube is the atmospheric or "static" pressure. The pressure in the Pitot tube is greater than this by the velocity head of the air $\frac{1}{2}\rho v^2$. This follows theoretically from Bernoulli's equation, assuming that a filament of air is brought to rest over the end of this tube, and is found to be at least very closely true in practice. The pressure gauge consists in essence of two vessels separated by a spring-controlled diaphragm of rubber, oiled silk, or corrugated metal, with a suitable mechanical magnification of the movement and a pointer moving over a dial calibrated in miles per hour (or knots) at standard sea-level density; so that if σ is the relative density, the instrument records $V\sqrt{\sigma}$, where V is the true speed through the air.

The Pitot and static tubes are commonly fitted in front of one of the front outer interplane struts. Errors in readings are introduced owing to the disturbance of flow by the aeroplane, and to the fact that the tubes

are rigidly fixed to the aeroplane and cannot lie along the lines of flow at any but one attitude of the aeroplane. The position described is probably the best practicable position for the pressure head for least interference, but errors of as much as 5 per cent on velocity may occur. For accurate work the air-speed indicator unit therefore requires calibration, and this is effected by flying the aeroplane at various speeds over a speed course, or sometimes by flying by the side of another aeroplane already calibrated over the speed course. (See next paragraph.) An attempt is being made to obviate the necessity for this speed course calibration by suspending the Pitot and static tubes at some distance below the aeroplane, stabilising this unit by suitable vanes.

The gauge part of this instrument requires calibration from time to time against a head of water. Those with metal diaphragms are the most satisfactory. The Pitot tube can be quite crudely made, but the static part must be fairly truly parallel over the part containing the small holes, and the holes must not be burred so that any metal projects outwards. It is not necessary to calibrate this, but merely to inspect the static tube. For experimental work, however, the instrument is calibrated as a complete unit in place on the aeroplane over a speed course.

Prior to 1915 the pressure gauge described was commonly replaced by a concentric U-tube filled with a coloured liquid of low freezing-point. This instrument, being "gravity controlled," has a calibration depending upon the acceleration of the aeroplane normal to the flight path, and it is easily seen that the readings give a measure of the incidence of the wings for accelerated as well as for steady motion. For some experimental purposes this would be of distinct value, but the instrument has fallen into disuse owing to its inconvenient square law scale, and the consequent closeness of the scale at low speeds. The static tube has been replaced in France by a small Venturi tube, and in this way a larger difference of pressure is obtained and a less sensitive pressure gauge is required. This instrument has the disadvantage that Venturi tubes in an open stream are sensitive to small changes of construction, and each Venturi tube requires individual calibration. There is, moreover, no difficulty in constructing pressure gauges of sufficient sensitivity and reliability for the Pitot-static combination. German aeroplanes have commonly been fitted with the anemometer already discussed, which measures the true air speed directly.

§ (4) The Speed Course.—For the calibration of air-speed indicators, speed courses of various forms have been employed. These essentially measure the rate of travel of the aeroplane over the ground, which is the resultant of the velocity of the aeroplane through the air (which it is desired to measure) and the velocity with which the air is moving over the ground. The "Ground Speed Course" at Farnborough is a simple form. Two huts, 1000 yards apart, upon a clear level stretch of ground, are fitted with pairs of vertical wires determining two vertical planes at right angles to the course, and are connected by electric bells for signalling. The aeroplane is flown alternately up and down the course a few feet above the ground, and the observer in each hut in turn starts his stop-watch as the aeroplane crosses his wires, and simultaneously signals to the other by pressing his bell switch, and stops his watch when the other signals the passage of the aeroplane past his wires. The other observer has also started his watch on hearing the bell and stopped it as the aeroplane passed his wires. By flying alternately in opposite directions the effect of the wind along the course is eliminated, but the effect of cross-wind must be allowed for. The true air speed is simply the resultant of the mean speed along the course and the cross-wind, and the latter is readily observed by means of an anemometer.

Two methods of dealing with cross-winds are available. In the first, the aeroplane is headed into the wind, so that it flies along the course, and correction is made for the cross-wind. The second method consists of heading the aeroplane in the direction of the course and allowing it to drift across the course with the wind. In this way the speed through the air is measured directly. The second method has been used on the ground course at Farnborough, and it is also used in America, and has the advantage of avoiding separate observations of cross-wind. On a long course, however, the drift necessitates a wide angle of observation, and for this reason on the "upper course" at Farnborough the first method is adopted.

The "Upper Speed Course" at Farnborough (*Fig.* 2) is similar in principle, but more elaborate apparatus is used, and the speed can be measured at any height at which observation from the ground is possible. At each station a horizontal telescope at right angles to the course fitted with a cross-wire and a 45° reflecting prism in front of the object glass determines a vertical plane across the course, and on the passage of the aeroplane an electric circuit is closed which marks a moving tape upon which time intervals are being marked continuously, both stations operating upon the same tape.

To observe the height of the aeroplane, a similar telescope at each station is arranged to rotate about its axis. The observer at the first station, after recording the passage of the

aeroplane across his vertical plane, follows it with this second telescope until the second observer presses his key as the aeroplane crosses his vertical plane, which automatically

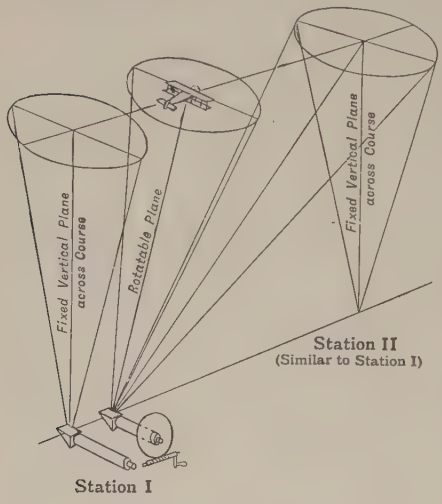

FIG. 2.—Diagram of Upper Speed Course (Royal Aircraft Establishment).

throws the rotating gear out of action. Each observer has thus to watch for the passage of the aeroplane across his fixed plane and to make his rotatable plane contain the aeroplane while it is crossing the other fixed plane in either direction. The height at each end is obtained in this way as the intersection of a vertical and an inclined plane. When the speed course is used for direct measurement of the speed of level flight, these height measurements are important to ensure that the aeroplane is flown level, any inclination of the path of course affecting the speed obtained. For purposes of calibration they are of less importance and simply provide a check upon the aneroid observations taken on the aeroplane. They are insufficient, as it is not merely the height but the atmospheric conditions of pressure and temperature which are required, and these must be obtained by readings of aneroid and thermometer taken by the pilot or observer in the aeroplane.

To allow for cross-wind the strength and direction of the wind at the height at which the aeroplane is flying must be observed, and for this a camera obscura is used. The motion of the air is made visible by firing a parachute light or a smoke puff from the aeroplane over the camera, and this drifts with the wind. The image of this is projected on to a sheet of paper by the lens of the camera and is marked down at intervals of time by the observer.

With this type of speed course the pilot has to keep his direction along the course and to keep his speed and height constant.

The speed course is clearly a problem which can be solved in a variety of ways, and different forms have been used, some of which have the advantage of allowing the pilot considerable latitude in the direction of flight. The original method used by the Testing Squadron at Upavon consisted of plotting the paths of the images of the aeroplane in two camera obscuras, marking down the images at intervals of time. The aeroplane may fly in any direction making an angle of at least 45° with the line joining the cameras. This method is, however, less accurate than that described above, and the observations require a more elaborate calculation to obtain the results. Moreover, the telescopes give a better definition than the camera, and the course can therefore be used on days of inferior visibility to those required for the camera obscura method. Also, it is difficult for the pilot to be certain when he is flying in the field of view of the cameras.

Similar in principle to the camera obscura speed course is the apparatus known as "Hill's mirrors." The cameras are replaced by plane mirrors marked in squares, and the image of the aeroplane is viewed by the observer through a fixed eyepiece.

The speed course forms the basis of all speed determination, but it cannot be used directly to measure speed except at low heights. Speed is measured at the greater heights by the instruments carried on the aeroplane, which are referred to the speed course for calibration.

§ (5) MEASUREMENT OF ENGINE REVOLUTIONS. — The instruments required on the aeroplane for performance tests are thus:

Air-speed indicator.
Thermometer.
Stop-watch.
Aneroid.
Engine revolution indicator.

Of these it only remains to discuss the engine revolution indicator. Formerly at Farnborough the revolutions were obtained by means of a counter used in conjunction with a stop-watch. Revolution indicators are of three main types, centrifugal, electromagnetic, and clockwork. The latter is most reliable, and is now used for experimental purposes. This instrument embodies a revolution counter and a clock which derives its motive power from the engine. It simply counts the revolutions over small intervals of time and indicates directly the revolutions per minute. If the revolutions change, the pointer moves in a series of jerks, but the time intervals are so small that the action is a sufficient approximation to continuity. This form of indicator is by its nature very reliable.

§ (6) The Climb Meter and the Statoscope.—As an aid to the pilot, to enable him to fly the aeroplane at the speed giving the greatest rate of climb, an instrument called a climb meter has been sometimes used. This (*Fig.* 3) consists of a "thermos" vessel connected with the atmosphere through a small leak formed by a length of capillary tube. This vessel forms one limb of a liquid U-tube manometer, the other limb consisting of a piece of magnifying thermometer tubing placed against a scale graduated in feet per minute of climb. As the aeroplane climbs, the atmospheric pressure changes and air leaks from the vessel, and the difference in pressure inside and outside the vessel is a measure of the rate at which the pressure is changing. This instrument can also be used as an aid in maintaining level flight when obtaining the level flight speed, being more sensitive than the ordinary aneroid for this purpose. A form of the climb meter designed only for maintaining level flight is known as the statoscope. The "bubble statoscope" (*Fig.* 3) consists of a "thermos" vessel

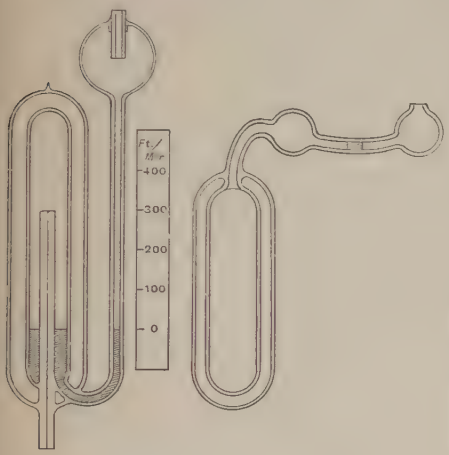

Fig. 3.—Climb Meter (left); Bubble Statoscope (right).

connected to a small bulb, from which leads a small-bore tube containing a drop of liquid, placed horizontally and curved slightly convex downwards, so that the centre is the lowest part, and terminating in a bulb open to the atmosphere. In level flight the drop of liquid remains at a fixed point in the tube, but a slight climb or fall of the aeroplane causes the air in the "thermos" vessel to change its volume and moves the drop to right or left, and a larger change of height forces the drop into one of the bulbs and allows air to escape or enter. The drop is thus in one of the bulbs during climb, and can be returned to the tube by causing the aeroplane to fall slightly, and the instrument is then ready for use as a level flight indicator. These instruments are not in general found necessary. The rate of climb varies but little, with the indicated air speed in the neighbourhood of the best climbing speed, and the pilot can guess the best speed with sufficient accuracy.

§ (7) Reduction of Performance to a Standard Basis for Comparison.—The observations taken at regular frequent intervals on a routine performance test are:

A. *Climb*—

(1) The aneroid height (*i.e.* pressure).
(2) The temperature.
(3) The rate of revolution of the engine.
(4) The time from start.
(5) The indicated air speed.

B. *Speed*—

(1) The indicated air speed at various heights flying level.
(2) The aneroid height.
(3) The temperature.
(4) The revolutions of the engine.

And, in addition, the weight and other particulars of the aeroplane.

In order to compare the performance of different aeroplanes under different atmospheric conditions, it is necessary to have some knowledge of the way in which the power of the engine varies with the atmospheric conditions. Let us assume for the moment that the engine power is independent of atmospheric temperature at a given atmospheric density. It is then only necessary to compare results at a given density in order to effect a true comparison. The results reduced on this basis express the performance of an aeroplane in the form of the speed of level flight and the rate of climb at various standard heights, and these figures give the speed and rate of climb at any height on any occasion on which the density is that of the standard height, although the observations from which these figures were deduced may have been taken at a very different true height.

§ (8) The Variation of Engine Power with Height.—Theoretical justification for the density law assumed above is to be found in the argument that the power developed by the engine, if the mixture is correctly adjusted, should depend upon the mass of the charge, and that this should be proportional to the density of the surrounding air. On account of the constant mechanical losses the horse-power delivered to the airscrew will decrease more rapidly than as the first power of the density, but will still be a function of density only. On the other hand, the charge is heated while being drawn into the cylinders, owing to the high temperature of the cylinder walls, which depends upon the explosion temperature and the method of cooling, and is therefore

not necessarily proportional to the atmospheric temperature. There is a mass of evidence showing that the power developed by engines depends upon the temperature as well as the density, in the direction of being a pure function of pressure. The law of variation may be expected to depend upon the design of the engine.

It is possible to investigate this variation by means of a very simple experiment. The torque required to drive an airscrew (propeller) at a given rate of advance per revolution is proportional to the product of the density of the air and the square of the revolutions per unit time. The airscrew can thus be used as a dynamometer consuming power of unknown amount but known law of variation. Uncertainty is only introduced by the possibility of the airscrew distorting with variation of atmospheric temperature. This appears improbable, and has been investigated in a refrigerating chamber without observing any distortion. Permanent warping between experiments can be observed by careful inspection on the ground between flights. The experiments must be carried out over as large a range of temperature at each pressure as possible. A more certain, but less simple, method of experiment is by the use of some form of torquemeter.

If the law of variation is established to be more closely a function of pressure than of density, a comparison of performance on a pressure basis should be made, as the error involved by reducing on the density basis becomes important for the more extreme temperature variations which occur in this climate. It can be shown that reduction to a standard atmosphere can be effected if the power variation is any known function of pressure and temperature. On the pressure basis the standard height is a pressure, and the performance figures express in effect the rate of climb and indicated air speed at a given pressure, the latter giving the true air speed only in the standard atmosphere. Strictly speaking, the rate of climb is that at a given indicated air speed, but the variation in rate of climb for small changes in air speed is small. If the law of variation is any function ϕ of pressure and temperature, the standard height is a value of ϕ.

§ (9) Up and Down Currents.—The most serious cause of error in the measurement of performance is the presence of vertical currents in the air. These may have a magnitude which is by no means small compared with the rate of climb of the aeroplane. If the climb path is plotted, it is often evident that the aeroplane has passed through an up or down current. Places, such as the sea coast, where vertical currents of considerable magnitude are known to occur regularly should therefore be avoided, and the tests should be repeated a number of times, and over different country so far as possible. Three climbs are usually carried out on routine performance tests, but for research purposes a very large number of observations are made. These are found in practice to be scattered rather widely, and only by obtaining a large number of observations can a mean curve be drawn with reasonable certainty, although the accuracy is not then of a very high order.

If, however, it were possible to determine at any moment the inclination of the aeroplane to the flight path and its inclination to the horizon, the difference between these two angles would give the inclination of the flight path to the horizon. When an aeroplane is flying in a vertical current, the inclination of the aeroplane to its path and of the path to the horizon are the same as in still air, but the rate of climb as measured by an aneroid from the ground is greater than the rate of climb through the air by the velocity of the current. The knowledge of the inclination of the path, however, coupled with a knowledge of speed along the path determines the required rate of climb through the air. This method of determining the rate of ascent has not so far been successfully applied, owing to the difficulty of determining the angle of incidence of the wings to the flight path arising from the extent to which the aeroplane disturbs the direction of relative air flow in its neighbourhood.

§ (10) Determination of Lift and Drag.—The lift and drag of an aeroplane at different angles of incidence of the wings may be determined by measuring the rate of climb at various air speeds. A large amount of work on these lines has been carried out at the R.A.E. The methods outlined above are employed for measuring speed and rate of climb. The incidence is determined by the use of a longitudinal inclinometer on the aeroplane. This consists of a spirit level which can be tilted by a micrometer screw so that the bubble can be brought central, and does not require any further discussion. The lift of the aeroplane is equal to the component of the weight normal to the flight path and very closely equal to the weight. The angle of incidence is obtained from the difference of the inclinometer readings and the angle of climb. The relation between lift, incidence, and speed is thus determined. In order to determine the drag the thrust of the airscrew must be known, and for this purpose the airscrew was calibrated on the "Whirling Arm" at the R.A.E. This whirling arm (*Fig.* 4) is a cantilever structure rotating about one end and carrying the airscrew at the other end. The arm is supported on trucks running on a circular rail at one-third of its length, and these carry electric motors which assist the airscrew in driving the

arm round. The airscrew is driven by an electric motor rated at 120 h.p. The arm is 150 ft. long and the airscrew can be driven forward at a speed of 80 m.p.h. at a rotational speed not exceeding 1200 r.p.m. The thrust and torque are recorded continuously by hydraulic dynamometers, and the speed of rotation of the arm and of the airscrew are recorded electrically. The speed of rotation of the arm is assumed to measure the mean speed of advance of the airscrew through the air over each revolution of the arm. Very calm weather is required for reliable results.

In this way the relation between the thrust of the airscrew and the forward and rotational speed has been obtained, if it be assumed that this is the same when running on the aeroplane as on the whirling arm, and that the airscrew does not warp. The drag of the aeroplane is the difference between the thrust and the component of gravity along the flight path. If it is desired to compare this with tests in a wind tunnel of a model without an airscrew, allowance must be made for the effect of the slipstream of the airscrew upon the drag of those parts of the aeroplane over which it passes. This effect has in practice been obtained by means of a suitable wind-tunnel experiment.

An alternative method of obtaining drag involves also the calibration of the engine upon a test bed. The engine is run on the bed on full throttle, and full throttle is used throughout the experiments. The power delivered by the engine can be tested before each flight by observing that it drives the airscrew at the same revolutions as when it first came off the test bed, or special "test-brake" airscrews calibrated upon an electric motor of known efficiency may be used at any time to check the power. The thrust of the airscrew is now determined from the engine calibration and the airscrew efficiency curve obtained on the whirling arm. This method has been thought to have the advantage that any distortion of the airscrew will affect its efficiency at a given rate of advance per revolution less than it will affect the relation between thrust, speed, and revolutions, and it was found that the engines used maintained a surprising constancy of power.

FIG. 4.—Whirling Arm at the Royal Aircraft Establishment.

§ (11) THE THRUST METER.—It is evident that some form of thrust meter is required to eliminate the uncertainties of the methods described above. The instrument at present in use at the R.A.E. has been tested against the whirling arm thrust meter before and after ten hours' flying, with agreement in both cases, and gives results in good agreement with other methods of deducing thrust. This thrust meter (*Fig.* 5) consists of two parts, A and B, fixed respectively to the engine shaft and to the airscrew. B is free to slide over A running on two rings of balls which form a front and a rear bearing. As B slides over A a helical spring between the front face of B and the front end of A is compressed. The drive is transmitted to the airscrew through a pair of ball-bearing rollers carried on the ends of a pair of arms on A. These rollers bear upon plane face plates attached to B. At the rear

of the airscrew a flange is formed upon B, and a lever pivoted on the engine crank-case carries at one end a small roller which bears upon this flange, being held up against it by a spring. The thrust moves B forward compressing the spring, and the lever follows this motion. The

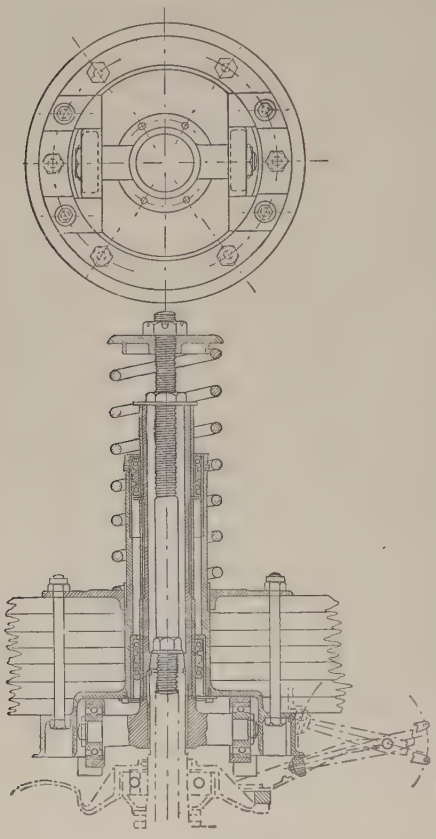

Fig. 5.—Thrust Meter.

displacement is transferred mechanically to a pointer moving over a dial in the observer's cockpit. The thrust meter is calibrated in a straightforward manner by pulling on the airscrew with a spring balance. This instrument, sliding entirely upon ball-bearings, is very free from friction. The only trouble anticipated was from wear of the hardened surfaces, flats appearing on the rollers or balls, or pits in the plane faces. This trouble has not, however, occurred.

§ (12) Lift and Drag by Glides.—For determining the lift and drag of the aeroplane for the important purpose of obtaining a direct comparison with wind-tunnel tests, the best method is by determining the rate of descent when gliding down with the engine shut off. As the variation of the drag of the airscrew with revolutions is of important magnitude, it is convenient to lock this so that it does not rotate. The airscrew can be stopped by switching off the engine and flying at as low a speed as possible. It is then locked by advancing a suitable obstruction against which one of the blades rests throughout the experiment. This can be readily withdrawn after the glide. The inclination of the path to the horizon is a direct measure of the ratio of drag to lift for the whole aeroplane, and can be compared with measurements in a wind tunnel upon a model, which may be an accurate replica of the aeroplane except that it is not practicable to represent the bracing wires upon the model.

§ (13) Airscrew Research.—The whirling arm has been employed to a limited extent for testing airscrews, but mainly in connection with the experiments described above. Owing to the rapid increase in horse-power and rotational speed of airscrews, this apparatus unfortunately became obsolete for testing service screws. If, however, the drag of an aeroplane is known and the engine calibrated on a test bed, this aeroplane can be employed for testing airscrews. Even if the drag is not known accurately, comparative results may be obtained on this aeroplane for a series of airscrews. The observations consist of engine revolutions and rate of climb at various indicated air speeds upon the lines already discussed.

The performance of the airscrew is dependent upon the extent to which the blades twist under load, and it is important to find the shape of blade which twists least. Some information may be obtained from the analysis of the results of tests of an extensive series embodying different blade shapes. So many factors are, however, involved in airscrew design, that it is desirable to develop some means of measuring twist directly in flight. It is proposed to use a camera rotating with airscrew to photograph the image of the sun in a pair of bright steel balls set on the surface of the blades; but so far little progress has been made with this line of research.

The measurement of the distribution of pressure over the blades of an airscrew in flight constitutes an important branch of airscrew research; but it has been thought more convenient to discuss this after the similar problem of determining the distribution of pressure over the wings of an aeroplane.

§ (14) Determination of Stalling Speed.—The methods of measuring the speeds which an aeroplane can attain in level flight, and the rate at which it can climb or must descend at any speed of flight at any height, have been described. It remains to discuss the determination of the lowest speed at which an aeroplane

can fly. As an aeroplane wing is set at an increasing angle to the direction of motion through the air, the lift of the wing at a given speed of motion increases in a manner very closely linear until a certain angle is reached, when the lift passes more or less suddenly through a maximum and begins to decrease. This angle is known as "the stalling angle," and an aeroplane flying at this incidence is said to be "stalled." It is clear that when an aeroplane is flying at this angle, it is flying at the lowest possible speed of steady flight. The "stalling" speed is of great importance, as upon it depends the speed at which the aeroplane must be landed. It is possible by reduction of wing area to increase the speed of an aeroplane, but the stalling speed is raised, and the difficulty of landing thereby increased.

The lowest practicable flying speed may easily be observed, but may depend upon the skill of the pilot, and may not be the same as the stalling speed, as both longitudinal and lateral control become difficult in this region. The actual stalling speed is of interest, as an improvement in the methods of control might enable this to be reached.

Although, however, a pilot cannot with certainty fly his aeroplane steadily at the stalling speed, he can easily fly through this state with an accelerated motion. Apparatus could be devised which should record the motion in such a way that the air speed and the lift of the wings at each instant could be deduced. The lift at a given angle of incidence is proportional to the square of the indicated air speed, and the maximum value obtained during the motion for the ratio of the lift to the square of the speed corresponds to the stalling condition. It is probably upon these lines that the accurate determination of stalling speeds will be made. It may, however, be found that the aeroplane stalls at a different speed when the incidence is changing at all rapidly, thus enlarging the field of inquiry. The effect of rate of change of incidence may be investigated by the method under discussion, but a rigid determination of the stalling incidence and lift will only be obtained when the difficulties of control at low speeds have been overcome.

§ (15) The Determination of the Possible Loads on the Aeroplane Structure in Flight.—The aeroplane designer requires to know what loads the various parts of the structure may be called upon to withstand in flight. In steady flight, the wings support the weight of the aeroplane, but during the violent manœuvres occurring in aerial fighting, the wings may be called upon to withstand at least three or four times this load. The maximum lift of the wings at any speed clearly occurs when the aeroplane is travelling at this speed with the wings meeting the air at the stalling angle of incidence. It is easily shown that the aeroplane is then describing the path of the least possible radius of curvature, and that this curvature is independent of the speed. Suppose that the speed is twice the stalling speed, then the load on the wings is four times the weight of the aeroplane. In order to determine experimentally the load which may occur during manœuvres, an accelerometer was designed at the R.A.E. by Professor F. A. Lindemann. This instrument (*Fig.* 6) is described below. It is also necessary for the designer to know how the load is distributed over the wings. Some years ago, M. Eiffel in his wind tunnel in Paris measured the distribution of pressure over a section of a model wing, and found that the greater part of the lift is due to suction over the upper surface, and that the load tends to be concentrated near the forward edge of the wing. About the same time similar wind-tunnel experiments by Professor B. M. Jones at the National Physical Laboratory determined the distribution of load completely

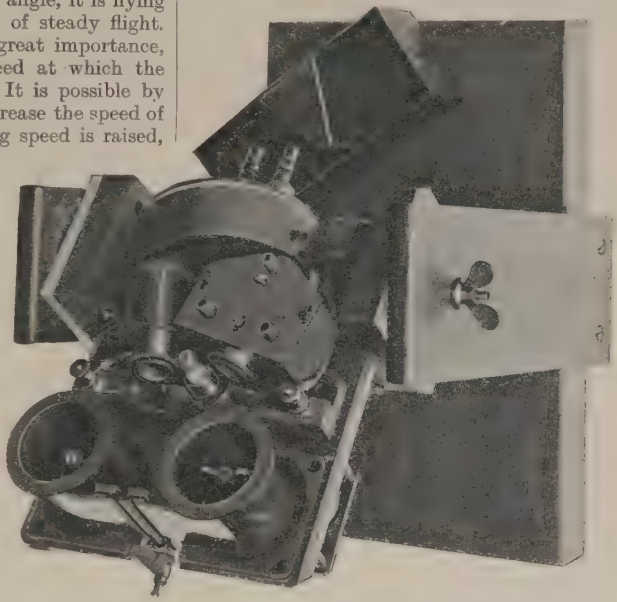

Fig. 6.—The Air-speed Recording Accelerometer. Air-speed recording gauge (left); time lamp (centre); accelerometer (right).

over a model wing, and showed the falling off of lift at the tip. Pressure measurements over a wing were first made in flight by Mr. G. I. Taylor at Farnborough, and complete full-scale determination of the distribution of pressure over the upper and lower planes of a biplane is now in progress. Measurements have also been made over a tail plane.

§ (16) The Accelerometer.—The accelerometer consists essentially of a mass attached to the frame of the instrument by an elastic support, and so proportioned that the free period is small compared with the period of any acceleration which it is desired to measure. In the R.A.E. accelerometer the mass and the elastic support are represented by a glass fibre bent in the form of a semicircle and fixed to the frame of the instrument at the two ends, thus forming a cantilever with its mass centre near the free end. The instrument measures accelerations normal to the plane of the semicircle. The free end is illuminated by a small electric lamp, and the image of this part of the fibre is projected on to photographic (cinema) film, through a narrow slit close against the film and at right angles to its direction of motion and to the plane of the fibre. This cuts the line image of the fibre down to a point. An additional lamp is arranged to mark the film either at the will of the operator or at regular intervals of time. The instrument is calibrated by turning it on to its back, and so obtaining the movement of the image corresponding to a reversal of the acceleration due to gravity. A complete calibration can be effected by mounting the instrument on a rotating table, but the scale is closely linear and the simpler method is sufficient for most purposes.

§ (17) The Air-speed Recording Accelerometer.—For many purposes it is desired to obtain a complete simultaneous record of air speed and normal acceleration, from which the curvature of the flight path can be deduced, and a combined instrument is now in constant use at the R.A.E. (*Fig.* 6). The air speed is obtained from the difference of pressure between the usual Pitot and static tubes, which are connected to a diaphragm gauge embodied in the same case as the accelerometer. The motion of the diaphragm actuates a lever which carries a short straight glass fibre between the prongs of a forked end. The image of this fibre is projected in the same manner as in the accelerometer on to the same film through the same slit. Actually two fibres are used in order to widen the scale, and it is arranged that the second image comes on to the film at the bottom shortly before the other passes off at the top.

§ (18) The Measurement of Pressure Distribution.—The measurement of the pressure on the surface of a body is effected by making small holes in the surface at the points at which the pressure is required, and connecting these holes by means of tubes passing inside the body to a suitable manometer. It is essential that these holes should be small, and that no obstruction should project round them outside the surface of the body. A sixteenth of an inch is a satisfactory diameter for these holes for full-scale work. If the tubes are allowed to project even to a very small extent through the surface, a local curvature of the flow is caused by the projection, which results in a lower pressure being recorded than the true one. On the other hand, a slight local concavity has not been found to have so serious an effect. For the determination of the distribution of pressure all over the wings, copper tubes have been fitted running the length of the wing, with branches serving the holes on the several sections to be explored. All the holes except those required at any time are closed by inserting short pins with suitable sealing material. The manometer used contains a number of glass tubes which are connected at their upper ends to the tubes in the wing and at their lower ends to a tank containing alcohol, which is arranged to stand at a convenient height in the tubes. Photographic paper is placed in contact with the tubes, and a record is obtained by switching on an electric lamp which throws a shadow of the meniscus on to the paper, the whole being contained in a light tight box. The paper is in the form of a roll, and can be wound on from a box on one side to a box on the other side. In the more compact of the existing designs the tubes are arranged in a semicircle, and in this case the two extreme tubes and the central tube are connected to the static tube of the aeroplane and provide the datum pressure. With this arrangement it is not necessary to maintain the manometer accurately vertical during use. Where all the tubes lie in one plane only two datum tubes are required, but in this case the plane in which the tubes lie must be kept vertical. One of the other tubes is connected to the Pitot tube, and in this way the speed of the aeroplane is recorded simultaneously with the pressure readings.

Apart from the labour involved by the number of observations which have to be taken in this class of work, considerable time is absorbed by the necessary frequent testing of the tubes for stoppage and air-tightness, and the preparation of the holes in use so as to get these accurately flush with the surface; so that the rate of progress with this kind of measurement is slow.

The value of the results extends considerably beyond the requirements of the designer

for calculating the necessary strength of the structure. They provide a very direct set of measurements for comparison with similar data obtained from tests of models in a wind tunnel. The total force normal to the wings and the position

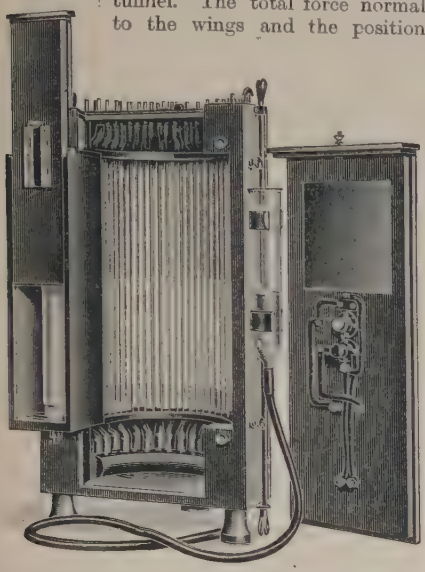

FIG. 7.—Semicircular Photomanometer. Opened to show tubes, etc., by removing sliding panel shown reversed on the right; paper box on right-hand side removed.

of the centre of pressure can be very closely determined by integration. This is, however, not true of the force acting along the chord of the wing, as the pressure measurements have determined only the forces acting normal to the surface, and an important part of the longitudinal force is due to tangential forces: at small angles of incidence the unmeasured forces may contribute one-third of the total drag. It is also to be noted that lift and drag, that is, the forces normal to and along the flight path, can only be deduced if the angle of incidence of the wing to the path is determined by some other method, as, for example, by the measurement of rate of climb and speed coupled with readings of an inclinometer as discussed above. The lift is very closely equal to the normal force, but the drag is composed of the longitudinal force and an important component of the normal force.

§ (19) DISTRIBUTION OF PRESSURE OVER THE BLADES OF AN AIRSCREW.—The methods of the last paragraph are now being extended to measurements over the blades of an airscrew, an experiment of fundamental importance from the point of view of the aerodynamic theory of the airscrew. Steel tubes are set in the wooden blades and covered over with veneer, and short branch tubes pass through the veneer to the surface. The manometer is mounted on the airscrew, rotating with it, and works on a rather different principle from that used for wing measurements. The pressures are in this case very much greater, and the compressibility of air is used to measure them. The manometer tubes are thin-walled glass capillaries closed at one end, and containing a bead of mercury whose position is recorded photographically as before. The position of the bead shows the expansion of the closed volume of air between the bead and the sealed end, and measures the pressure at the hole on the blade when correction is applied for the centrifugal head due to rotation. The two principal difficulties encountered are, firstly, the tendency of the bead to flatten out, due to the rotation, and so fail to fill the bore of the tube, and secondly, that this necessitates a small bore in which the mercury bead will not move freely. It has been found within the limit of bore necessitated by the first consideration that the bead will move sufficiently freely if the tube and bead are covered by a film of liquid, and for this purpose cresol has proved satisfactory. The record is taken by discharge through a vacuum tube which provides a uniform illumination along the capillaries, and the paper is wound on by means of a windmill brought into action by an electromagnetic clutch under control of the experimenter.

§ (20) THE STABILITY OF THE AEROPLANE. (i.) *Equilibrium Conditions.*—A discussion of stability must logically be preceded by consideration of the conditions of equilibrium. In the case of the aeroplane, this involves equation of forces along and moments about some three co-ordinate axes. The aeroplane is, however, approximately symmetrical about the vertical plane containing the flight path in straight, steady flight. Asymmetry is caused by the airscrew. The airscrew torque must be balanced either by a permanent asymmetric rigging of the wings or by a small displacement of the ailerons — the control surfaces employed for lateral balance. In addition the flow in the slipstream is of a spiral nature, and if the fin and rudder—the vertical tail surfaces employed for stabilising and controlling the direction of flight—are not symmetrically placed in the slipstream, a turning moment is produced by the slipstream. In some aeroplanes this calls for a heavy force on the rudder in order to maintain a straight course. An aeroplane fitted with a pair of engines, one on either side of the centre, is asymmetrical when flying with one engine wholly or partially out of use. We may, however, for general discussion treat the aeroplane as symmetrical about this vertical plane.

The equation of forces consists, therefore, of equating the lift of the aeroplane to the component of the weight normal to the flight path, and the thrust of the airscrew to the drag of the aeroplane, and the component of the weight along the path. There are no lateral forces. The moment about the horizontal axis perpendicular to the path must be zero. This is known as the pitching moment, and the required condition is obtained by setting the tail planes at suitable angles. These consist in most aeroplanes of a fixed part (the tail plane), and a movable part (the elevators) controlled by the pilot. The setting of the fixed part determines the angle of incidence of the wings at which the aeroplane "trims" with the elevators free, and thus determines the trimming speed "hands off." The tail plane is often arranged to be adjustable by the pilot in flight, and thus relieve the load on the elevators and consequently on the pilot's hand, for any desired condition of flight. The remaining moments, known as yawing and rolling, are zero on the assumption of symmetry without any adjustment of the controls.

The equilibrium conditions will be discussed in more detail later, under the heading of "Control." This order is followed because the control is so largely dependent upon the degree of inherent stability or instability of the aeroplane. An aeroplane possessing a strong will of its own obviously calls for greater exertion on the part of the pilot to control it.

The aeroplane is stable if, from any small displacement, it tends to return to the original state of steady motion. The mathematical theory of stability [1] has been developed by Professors G. H. Bryan and L. Bairstow. It has been shown that motion in the vertical plane of symmetry can be treated separately from other motions, but that the lateral, yawing and rolling motions, cannot be separated. These two stabilities are known as "Longitudinal" and "Lateral" stability, and will be discussed separately. When an aeroplane is pitched, yawed, or rolled from the equilibrium state, it is a necessary condition of stability that there should be a restoring pitching, yawing, or rolling moment; but an aeroplane having a restoring yawing or rolling moment cannot be said to be "directionally" or "laterally stable" as the two motions are interconnected; also a restoring pitching moment does not completely determine longitudinal stability.

The theoretical work of Bryan and Bairstow was applied practically by the late Mr. E. T. Busk, who made the B.E.2c. aeroplane longitudinally stable and demonstrated its stability in 1914 by flying from Farnborough to Salisbury Plain with the longitudinal control abandoned.

[1] See "Aeroplane, Stability of."

(ii.) *Longitudinal Stability.* — Suppose that the pilot of an aeroplane in steady flight varies his speed by a movement of the elevator and quickly returns the elevator to the initial position. Longitudinal stability will be shown by the aeroplane executing a convergent oscillation, returning finally to the initial speed. During this motion the air speed and the incidence oscillate about the initial values. The simplest method of experiment requires no special instruments. The pilot, or an observer on the aeroplane, notes the air speed at regular small intervals of time (say every five seconds). From these readings the period of the oscillation and a measure of the damping can be obtained. This method is employed at the R.A.E., but the air speed recording instrument described above is now used. The Royal Air Force Testing Squadron at Martlesham Heath employ a rather different method, observing the incidence instead of the speed. For this purpose a special form of camera is fixed to the aeroplane, which is flown towards the sun, which must be fairly low. A cylindrical lens produces a line image from the sun, and this is projected through a transverse slit on to moving photographic paper, and the path of the point image so produced gives a record of the varying inclination of the aeroplane to the horizontal.

The presence or absence of a restoring moment and the magnitude may be deduced from observations of the change in the force which the pilot must exert, and of the movements of the elevators required to alter the speed of the aeroplane by some small amount, as a knowledge of the direction and magnitude of the force which the elevators must exert to change the speed shows the inherent tendency of the aeroplane in this respect.

(iii.) *Lateral Stability.*—Longitudinal stability is of greater practical importance than lateral, in part because a longitudinally stable aeroplane may be flown with the pilot's hands off the longitudinal control, whereas lateral stability does not permit abandonment of the rudder for long, as the inevitable small asymmetry of the aeroplane requires continual operation of the rudder in order to steer a straight course. It is of course desirable that the aeroplane should not be violently unstable; but many types of aeroplane are unstable in every way, and small instability is even thought desirable by many pilots. The investigation of lateral stability also presents greater difficulties, and for these reasons less has been done on this branch of the subject. An instrument due, in its simplest form, to the late Dr. Keith Lucas, has been used for recording the motion of an aeroplane with the controls locked or abandoned. This is essentially

a pin-hole camera producing an image of the sun, and very similar to the camera used subsequently at Martlesham Heath and described in the last paragraph. In the form used at the present date at the R.A.E. the "Photo-kymograph" is mounted for use with the sun on the side of the aeroplane and records angular movements about the longitudinal and the vertical axes—respectively roll and yaw. One of these two displacements must take place in the direction of motion of the photographic paper, and it is therefore necessary to mark time intervals along the trace. This is effected in the following manner. During the greater part of the time an orange glass is interposed which allows only sufficient light to pass to mark the paper faintly. At small intervals of time this is withdrawn by a clock for a fraction of a second, and a dark point is produced on the trace. Simultaneously a pair of datum lines at right angles are marked on the paper. This is effected by light passing through a cruciform slit placed close against the paper.

An alternative method of recording the angular motions of an aeroplane is by means of the gyroscope. A gyroscope mounted in gimbals so as to be perfectly free maintains the direction of its plane of rotation fixed in space, and can therefore be used to record angular motions of an aeroplane about two axes. This method is at present being developed. It is proposed to use two gyroscopes, electrically driven, with their axes of rotation at right angles, recording optically upon photographic film. The range of usefulness of the gyroscope is limited in this way: when the aeroplane has moved so that the axis about which the gyroscope is to record the motion coincides with the axis of rotation of the gyroscope, the gyroscope is no longer capable of recording the motion. The instrument, as proposed, will be capable of recording a complete turn about the vertical axes so long as the aeroplane is not inclined longitudinally or laterally to the vertical at an angle exceeding 45°. This is, however, sufficient to meet the requirements for stability measurements.

A gyroscope instrument is, however, in use for lateral stability experiments as an aid to the pilot when it is desired to fly straight, or at a given steady rate of turn. This is the R.A.E. Gyro Turn Indicator, and has been developed as a standard instrument for use in flying through clouds. The gyroscope is placed outside the aeroplane in the air stream, and is so shaped that it is directly wind driven. It revolves about an axis parallel to the direction of motion and is free to rotate about the horizontal transverse axis under the control of a spring. When the aeroplane turns about the normal axis, the gyroscope moves rigidly with it, and deflects the spring by a small amount sufficient for this to provide the couple required for the rate of turning. The deflection of the spring is indicated on a dial, and is a measure of the rate at which the aeroplane is turning.

§ (21) The Control of the Aeroplane.—The control of an aeroplane can be effected by means of horizontal and vertical directing surfaces known as the elevator and the rudder. These are generally placed behind the wings, but this is not essential, and in some of the early aeroplanes the elevator was placed in front. Several of the earlier aeroplanes depended on these controls alone. In turning, use of the rudder caused the aeroplane to sideslip and the aeroplane then "banked" itself, owing either to the provision of a fin surface above the centre of gravity, or to the wings being inclined at a dihedral angle, *i.e.* inclined upwards from root to tip. The Wrights obtained better control on their aeroplane by providing a means of lateral balance by warping the wings. The "ailerons" used now are a mechanical improvement, but similar in principle. These consist of a portion of the wings at the rear near the wing tip, which are hinged to the main part of the wing and can be deflected together in opposite directions on the two sides. This additional control is essential for rapid manœuvring. During a rapid turn the aeroplane is banked until the span of the wings becomes almost vertical and the lift of the wings is mainly counteracting "centrifugal force." Under these conditions the functions of the control surfaces are more or less reversed. It is the elevator which determines the radius of turn and the rudder which controls the air speed. It is easily shown that an aeroplane has a least possible radius of turn equal to V_s^2/g, where V_s is the stalling speed, and that this is independent of the speed at which the turn is made.

The question of controllability involves two distinct ideas. In the first place, the effectiveness of the control surface, when moved to the most effective position possible, must be considered. The limitation of effectiveness may be aerodynamic—the surface may "stall"—or it may be mechanical, depending upon the design of the aeroplane. In the second place, we are concerned with the effort required of the pilot. This depends upon the aerodynamic properties of the control surfaces and the size of the aeroplane, and upon the gearing employed between these and the pilot. We are concerned both with the force the pilot must exert and with the movement he must make. If the force is large and the movement small, an improvement may be effected by altering the gearing.

§ (22) Longitudinal Control.—Following the procedure adopted in discussing stability, longitudinal control may be considered here separately in the first place. The three principal factors requiring investigation for both longitudinal stability and longitudinal control are the relative position of the centre of pressure on the wings and of the centre of gravity of the aeroplane, the angle through which the air-flow at the tail has been deflected by the wings, and the aerodynamic properties of the tail. The first gives approximately the force which the tail must exert. The centre of pressure may be determined by the pressure distribution experiment described above, but this is an extremely laborious method.

(i.) *Centre of Pressure on Wings.* — The position of the centre of pressure upon a number of sets of wings has been investigated

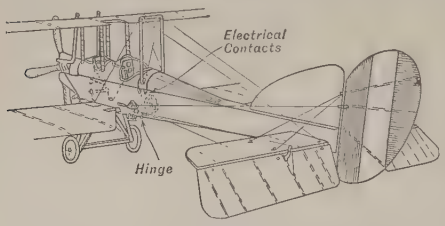

Fig. 8.—Aeroplane with Jointed Body, used for measuring the Reaction on the Tail.

at the R.A.E. upon an aeroplane (*Fig.* 8) which had its body broken behind the two cockpits and hinged by a pair of ball-bearings, stops being provided to limit the possible movement. Suitable bracing enabled the moment of the forces acting upon the parts of the aeroplane behind this hinge to be transferred to a spring balance in the observer's cockpit. The observer is able to float the rear part of the aeroplane by adjusting a turnbuckle below the balance until neither of a pair of electric lamps is alight, these lamps being operated by a pair of electric contacts which are made as the rear part approaches the stops which limit its movement. Allowing for the weight of the parts, this experiment gives almost directly the air force acting upon the tail. To deduce the position of the centre of pressure on the wings, an estimate must be made of the forces on the airscrew, front part of the body, and the landing-gear. For this purpose wind-tunnel tests have been employed.

(ii.) *Tail Plane Characteristics.*—The angle of downwash at the tail cannot be measured directly, as the flow at the tail is disturbed by the presence of the tail plane. It can be deduced if the tail force and the aerodynamic characteristics of the tail plane are known. Although the angle at which the tail plane meets the air is unknown, the tail characteristics can be determined by a series of experiments in flight involving very simple apparatus. The aeroplane is flown at various speeds, with the fixed tail plane set at different angles and the position of the elevators is observed. For this purpose the movement of the elevators is transferred by a light cable to a pointer moving over a scale in a convenient position in the cockpit. These measurements determine directly the elevator movements which give the same change in tail force as given alterations in the setting of the tail plane. The aeroplane is then flown with a weight attached at the tail, and the position of the elevators noted at different speeds, thus relieving the tail plane of a known amount of load. In this way the rate of change of tail force with tail plane and elevator angles is determined, and if this unit is of symmetrical section (as is commonly the case) the tail characteristics are completely determined. If the force which the tail must exert has been determined by the experiment described in the last paragraph, the remaining unknown quantity, the angle through which the flow has been downwashed by the wings can be directly obtained. The actual flow at the tail is complicated, in particular by the action of the airscrew, and the downwash determined is an "effective downwash" and may vary to some extent with the form of the tail plane.

The remaining quantity of importance in longitudinal control is the moment of the air force upon the elevators about their hinges, upon which depends the force which the pilot must exert to hold the aeroplane at various speeds. This is obtained by means of a special form of spring balance. A flat cantilever spring is clipped to the top of the control column and the elevators are operated through this spring. The deflection of the spring is measured by means of an "Ames Dial," an instrument in use in engineering workshops for making fine measurements. This is graduated to read directly the pull or push exerted by the pilot's hand.

(iii.) *Effects of the Airscrew Slipstream.*—The slipstream, or current of air projected rearwards by the airscrew, has important effects upon stability and control. The tail surfaces are commonly so placed that this stream flows over them. The effectiveness of the tail unit as stabiliser and for control is thus increased when the airscrew is in action. The forces on the tail are increased and the trimming speed is consequently changed when the engine is opened out. Longitudinal stability is obtained principally by placing the centre of gravity well forward, and this generally involves a considerable down load on the tail. In a very stable high-powered aeroplane the change of trim from

engine on to engine off may therefore be large. It is also desirable that the fin and rudder should be symmetrically placed in the slipstream in order to avoid the turning tendency produced by the helical nature of the flow upon surfaces placed unsymmetrically. It follows that a knowledge of the nature and position of the slipstream at the tail is a matter of considerable importance.

(iv.) *Slipstream Exploration.*—The speed of the air-flow over a plane in front of the tail plane, including the slipstream, has been explored by fixing a number of Pitot and static tubes on a light outrigger and connecting these tube. These instruments require individual calibration in a wind tunnel. Three are being used together, mounted upon an arm along which they can be moved when the aeroplane is on the ground (*Fig.* 9). This arm can be rotated round the body of the aeroplane in flight. The tubes are connected to the photomanometer. It is thus possible to obtain in one flight the velocity and direction at a number of points upon three circles, and in a number of flights to cover the whole region to be explored.

§ (23) Lateral Control.—The rate at which an aeroplane can be turned depends upon the

Fig. 9.—Apparatus for measuring the Speed and Direction of Flow in the Slipstreams of the Airscrews, fitted to a large Twin-engine Aeroplane; showing the rotatable arms carrying the five tube instruments.

to the photomanometer used for the pressure distribution experiments. This outrigger was horizontal and was moved vertically between each flight. A more complete experiment now in progress aims at determining simultaneously the velocity and direction of flow. The determination of direction is based upon the fact that the pressure in an open-ended tube when inclined at about 60° to the direction of flow is very sensitive to small changes of direction. The instrument used consists of five open-ended tubes, four of which are equally spaced round a cone of semi-vertical angle about 60°, and the remaining tube lies along the axis of the cone and acts more or less as a Pitot tube. The inclined tubes in pairs constitute yaw and pitch meters, and together replace the usual static

radius of the least turning circle discussed above, and the speed of the aeroplane, and in this respect the more lightly loaded aeroplane is the more manœuvrable. It depends also very largely upon the rate at which the aeroplane can be banked for the turn. The camera obscura has been used for plotting the horizontal projection of the path during turning, and the air-speed recording accelerometer may be used for measuring the curvature of the path in any plane, and therefore for investigating turns, loops, or any other manœuvre. It is also possible to observe from the aeroplane the time taken to turn through a given angle gauged by some objects on the ground. The comparative merits of several aeroplanes in respect of lateral control has been investigated by the rather

crude method of measuring with a stop-watch the time taken to bank 45°, gauged by eye against the horizon, starting the watch when the control column was pushed over. Readings were found to vary as much as 1 sec. in 3 sec. under apparently identical conditions with the same aeroplane and pilot, but by repeated observations the aeroplanes were probably placed in the correct order of merit. These experiments included measurements of the mean force exerted by the pilot read by the pilot by means of the instrument described under "Longitudinal Control." Such crude methods are clearly inadequate. For a satisfactory investigation of manœuvres and control, apparatus is required to record against time the three angular movements of the aeroplane, the movements of all the control surfaces, and the forces applied by the pilot to each control. Different pilots handle aeroplanes in different ways, and the same pilot will handle different aeroplanes differently, and cannot be relied upon always to repeat manœuvres even on the same aeroplane in exactly the same manner. It therefore becomes desirable to observe the behaviour of the aeroplane under the action of known constant forces applied by special mechanism to the controls, and at the same time to investigate the methods employed by as large a number of pilots as possible by means of the recording apparatus outlined above. At the same time the air speed and the angle of sideslip of the aeroplane should be recorded. The pilot may be instructed to turn without sideslipping, but even if he could do so with certainty, this does not necessarily represent his usual method, or the best method of turning.

§ (24) Use of the Cinematograph Camera.—At the R.A.E. a cinema camera (*Fig.* 10) has been used to photograph the manœuvres of an aeroplane from another aeroplane. The aeroplane carrying the camera is flown in a straight level path, and the aeroplane under observation executes the required manœuvres behind this. The camera is suitably mounted on the aeroplane so that it can be trained in any required direction over a considerable range. Sighting gear is fitted which enables the observer to move the camera so as to keep the aeroplane in its field. The movements of the camera about the vertical and horizontal axes are recorded on the film by suitable photographic means. About twenty pictures a second are taken, but only a fraction of this number is actually required. Angles are measured from the picture as required, and the attitude of the aeroplane is calculated from these by the use of a graduated sphere (*Fig.* 11), which reduces the labour of transformation to the required axes to a small fraction of what would be required by direct calculation.

§ (25) Use of Gyroscopic Methods.—The problem of recording the movements of an aeroplane during rapid manœuvres is also being

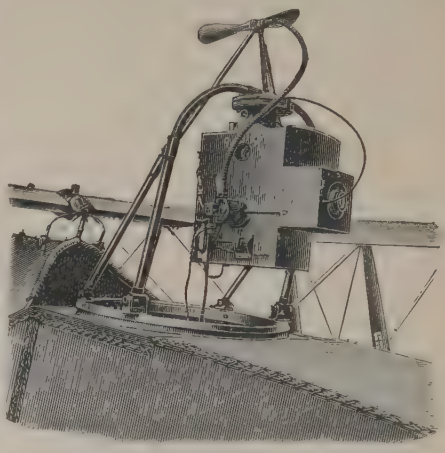

Fig. 10.—Cinematograph Camera mounted on an Aeroplane.

attacked upon different lines with the intention of replacing the cinematograph in time by a gyroscopic instrument. This will eliminate the need of a second aeroplane with the camera, and give more directly, and more

Fig. 11.—Sphere used for Calculations.

accurately, the readings required. The proposed gyro instrument operates on a different principle from that proposed for stability work, as the displacements are in this case large and the movements rapid. The rates of change of angles are the quantities really required, and the gyro instrument will

read these directly. It will consist, in fact, of three recording instruments, similar in principle to the gyro turn indicator described under "Lateral Stability" above. Three gyros revolving about perpendicular axes are to be mounted so that they precess with the aeroplane. Each gyro will obtain the couple required for the precession by deflecting a small amount under the control of a spring about the axis perpendicular to its axis of revolution and the axis about which it measures the angular velocity of the aeroplane. The deflections of the three gyros will be recorded optically upon the same photographic film. The gyros will form the rotor of small induction motors, so that no brush gear will be present to introduce friction. They will take current from an alternator driven by a windmill, and some means must be provided for maintaining the speed of this generator constant, however the speed of the aeroplane may vary. This may be achieved by a combination of a centrifugally operated variable-pitch windmill, coupled with a centrifugally controlled slipping clutch, or by means of a direct current generator and motor with a buffer battery. This remains a matter for experiment.

driven by a small windmill through an electromagnetic clutch. This clutch can be operated by the experimenter, and is also controlled by a small centrifugal governor so that the film shall run at constant speed. In an alternative design metallic paper is used and is driven by a pair of pawls and a ratchet operated alternately at half-second intervals by an electromagnet which is energised whenever contact is made in the electric circuit by a master clock.

The ailerons and elevators of the smaller aeroplanes are operated by the sideways and

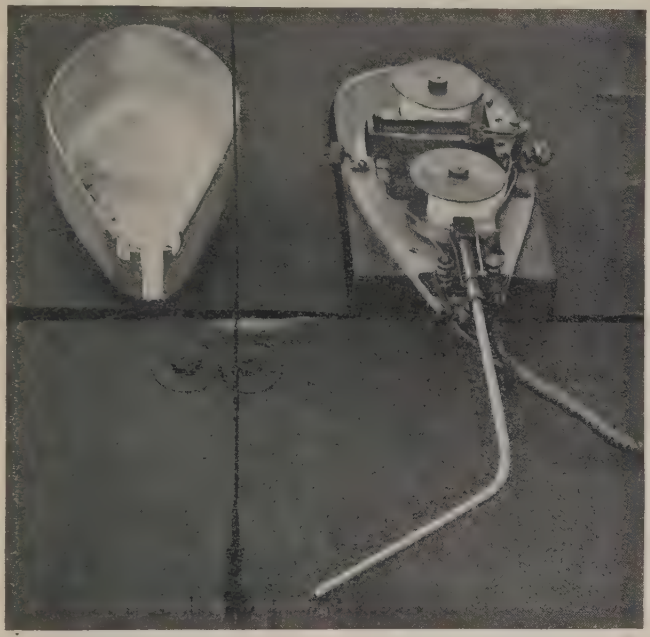

Fig. 12.—Instrument for recording Movement of Control Surfaces.

§ (26) Control Recording Instruments.—A compact and thoroughly reliable instrument is required to take a simultaneous record of any displacement and of intervals of time, with some means of synchronising with other instruments and capable of operating in any position on an aeroplane. Work has been proceeding on this for some time, but a satisfactory instrument has not yet been obtained. This instrument would be used to record the movements of control surfaces, and for this purpose would be fixed to the aeroplane close to the surfaces and operated directly by them, eliminating slack and stretch in the control cables, etc. In the most promising design in hand (*Fig.* 12) the displacement and the time intervals are recorded optically upon photographic film which is

fore-and-aft movement of a universally pivoted lever known as the "Control Column." A special control column (*Fig.* 13) has been designed which can be fitted in place of the ordinary lever on any aeroplane, or attached to it. This records the force exerted by the pilot's hand in both directions. The force is applied by the pilot's hand to a knob universally pivoted by gimbals at the top of the column. The column is universally jointed by gimbals lower down, and a steel cantilever projects from the lower part to which it is rigidly attached, coming into contact with the upper part through a spherical knob at its end. A continuation of the upper part projects downwards inside the lower part, carrying an electric lamp and pinhole at its end close above photographic film run through the

lower part by means of a small electric motor. As in the photo-kymograph, where two perpendicular displacements are recorded directly on the same film, the record is not continuous. At short intervals of time a clock is arranged to switch off the recording lamp momentarily and actuate simultaneously a second lamp which illuminates the width of the film through a transverse slit. We thus obtain readings of the two forces at every instant at which the recording lamp is switched off, by measuring the co-ordinates of the beginning of the break in the trace with

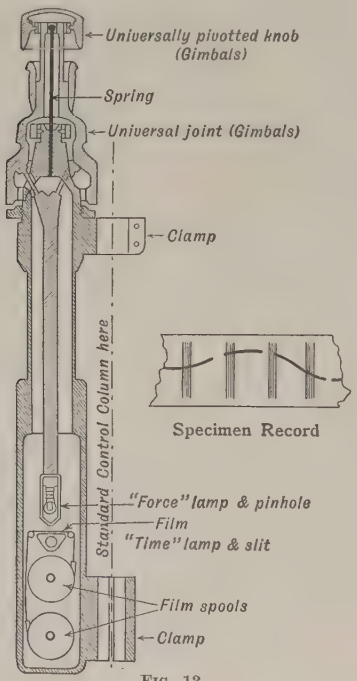

FIG. 13.

reference to the beginning of the dark band on the film produced by the second lamp through the slit. For some purposes it will be more convenient to employ a simpler form of this instrument which records only the force in one direction, and can record this continuously. For example, to determine the relative merits of different types of aileron fitted to the same aeroplane, it is sufficient to observe the force applied to the ailerons only if the movements of all the controls are measured.

§ (27) APPARATUS FOR APPLYING A KNOWN CONSTANT FORCE TO THE CONTROLS.—As stated in the general discussion above, it is desirable to be able to observe the behaviour of an aeroplane when a known constant force is applied to one of the controls. The apparatus designed for this purpose contains a number of springs of varying strength with suitable selecting gear and means of straining them to a definite extent. The load is applied through a cam so shaped that the force remains constant as the control moves over and the tension in the spring is eased. In use the observer selects and strains the springs, and the pilot takes the strain holding the control central. The pilot reads the force on his hand by means of the force-measuring instrument described under "Tail Plane Characteristics," and then abandons the control to the strained springs.

§ (28) OBSERVATION OF SIDESLIP AND LATERAL ACCELERATION.—Every British aeroplane is fitted with an insensitive form of spirit level set across the aeroplane, which serves to some extent as a sideslip indicator. This actually measures the ratio of the lateral to the normal acceleration, or the apparent direction of gravity. When the rudder is used to produce a turning moment, the aeroplane must sideslip to the extent necessary to produce an equal and opposite force to that on the rudder. This does not affect the "bubble." Apart from this any sideslip moves the bubble, as it produces a side force on the aeroplane, and the bubble is therefore an indicator, although not a measure of abnormal sideslip. So long as the bubble is central on a turn, the aeroplane is commonly said to be "correctly banked." When flying straight with sideslip the aeroplane must be "one wing down," and the bubble reads the extent to which the wing is down, but its reading is incorrectly, though frequently, spoken of as the angle of sideslip.

A yaw meter is in use at the R.A.E., which consists of a pair of open-ended tubes inclined one on either side at an angle of about 60° to the direction of motion. The difference between the pressures in these two tubes is a measure of the angle of yaw or sideslip, although it also depends upon the air density and the speed of flight, and must therefore be used in conjunction with the air-speed indicator. This instrument requires individual calibration in a wind tunnel.

The accurate investigation of manœuvrability and control is a matter of great complexity, and one which is still in the state of development of the apparatus required for recording the many quantities which require observation. Investigations in the immediate future will of necessity be carried out without all the refinements of measurement which are desirable.

[The writer wishes to acknowledge his indebtedness to his colleague, Mr. H. L. Stevens, for his very

helpful criticism of this article and for some valuable suggestions.]

R. M'K. W.

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„ 547. Resistance of an aeroplane determined by glides with the propeller stopped.
„ 567. Tests of swivelling pressure heads.
„ 576. Analysis of phugoids obtained by a recording airspeed indicator.
„ 608. Reduction of aeroplane trials for the purposes of aerodynamic comparison and prediction.
„ 610. Errors of the readings of altimeters and airspeed indicators due to variations of temperature of the air.
„ 636. Control as a criterion of longitudinal stability.
„ 641. Maximum control of elevators of different sizes.
„ 659. Full scale determination of the lift and drag coefficients of biplanes by means of engine and airscrew performance.

AEROFOIL THEORY OF AN AIRSCREW: a theory based on the hypothesis that an airscrew blade may be regarded as an aerofoil of a form suitable to glide in a helical path, the performance of the airscrew being calculated from an integration of the forces acting on elemental strips of the blade, such elemental forces being estimated from aerofoil data measured directly in a wind channel. See "Airscrew, The," § (2).

[1] This paper includes an account of early measurements of pressure distribution over wings in flight.

AEROPLANE, COMPONENT PARTS OF AN

IF a flat surface of any shape placed so as to make a small angle with the horizontal plane be driven through the air in a horizontal direction with its upper edge in front, the air pressures on the under side of the surface exceed those above and the surface experiences an upward force—a *Lift*—tending to raise it and oppose its weight; it also experiences a horizontal force—a *Drag*—which resists the horizontal motion. If the speed with which it moves be sufficient the lift will balance its weight and the surface will remain suspended in the air, the surface will fly. Modern (heavier-than-air) aircraft make use of these facts and have been developed so as to become efficient flying machines. The surface—the wing of the machine—takes the form in plan of an elongated rectangle—the ends are frequently rounded—with its greatest length at right angles to the direction of flight; it is no longer flat, the upper side has considerable curvature or *Camber*, rising somewhat sharply in front along the *Leading Edge* and tapering gradually to the rear, the *Trailing Edge*. The under side is more nearly flat and is usually slightly concave.

Fig. 1 gives the form of a vertical section of some typical wings taken at right angles to

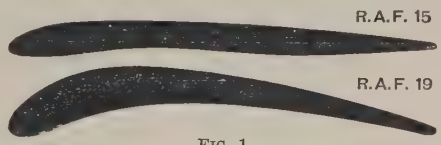


FIG. 1.

the leading edge, while *Fig.* 2 is a skeleton drawing of an aeroplane on which the various parts are indicated. The wing when considered apart from the rest of the machine is spoken of as an *Aerofoil*.

A line drawn from the leading to the trailing edge at right angles to the length of the wing is known as the *Chord*, while the distance from tip to tip measures the *Span*. The ratio of the span to the chord gives the *Aspect Ratio* of the wing. The lift on the wing depends greatly on the shape of the section and is influenced by variations in the upper surface to a greater extent than by modifications of the lower side. It also depends on the aspect ratio, and for a given wing area is increased by increasing this quantity.

The wings are attached to the body of the machine, projecting from it at right angles to its length.

The two wings, right and left, do not lie in the same plane, but are inclined to each other at an angle which does not differ much from

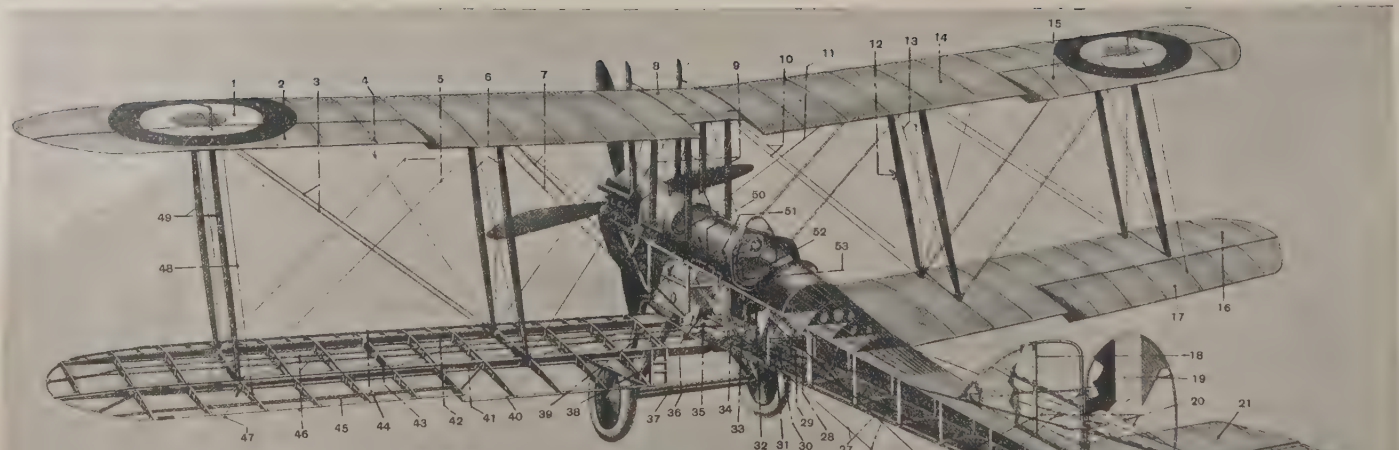

1 PORT UPPER MAIN PLANE.
2 PORT UPPER AILERON.
3 OUTER FLYING WIRES.
4 AUXILIARY FLYING WIRE.
5 OUTER LANDING WIRES.
6 INNER INTERPLANE STRUTS.
7 INNER FLYING WIRES.
8 CENTRE SECTION UPPER PLANE.
9 CENTRE SECTION STRUTS.
10 INNER LANDING WIRES.
11 DRAG CABLE.
12 PRESSURE HEAD.
13 INCIDENCE OR STAGGER WIRES.
14 STARBOARD UPPER MAIN PLANE.
15 STARBOARD UPPER AILERON.
16 STARBOARD LOWER MAIN PLANE.
17 STARBOARD LOWER AILERON.
18 FIN.
19 RUDDER.
20 TAIL PLANE BRACING WIRES.
21 TAIL PLANE.
22 ELEVATOR.
23 RUDDER POST
24 SKID POST.
25 TAIL SKID.
CONTROLS.
26 SKID CONTROL WIRE.
27 ELEVATOR CONTROL CABLES.
28 ELEVATOR CROSS SHAFT TUBE.
29 ELEVATOR OPERATING LEVER.
30 ELEVATOR CONNECTING TUBE FROM CONTROL COLUMN.
31 ELEVATOR CONTROL LEVER.
32 PILOTS CONTROL COLUMN.
33 RUDDER CONTROL CABLES.
34 RUDDER ROCKING BAR.
35 RUDDER BAR.
36 AILERON CONTROL GEAR.
37 UNDERCARRIAGE AXLE.
38 UNDERCARRIAGE REAR STRUT.
39 UNDERCARRIAGE FRONT STRUT.
40 TRAILING EDGE.
41 REAR SPAR.
42 FRONT SPAR.
43 COMPRESSION RIB.
44 LEADING EDGE.
45 PORT LOWER AILERON.
46 STRINGERS.
47 MAIN PLANE SKID.
48 AILERON CONNECTING WIRE.
49 OUTER INTERPLANE STRUTS.
50 HAND PRESSURE PUMP.
51 ENGINE SWITCH.
52 PETROL CONTROL.
53 THROTTLE LEVER.

FIG. 2.

180°. Imagine the machine placed with its plane of symmetry vertical, so that each half of the wing is equally inclined to the horizon. The angle between the wing and a horizontal plane is known as the *Dihedral Angle*.

If the machine has one wing, or rather one pair of wings, it is a *Monoplane*. A *Biplane* has two pair, one mounted above the other, a *Triplane* three pair, and so on.

In a multiplane the wings are held apart by *Struts*; the whole framework is strengthened by *Bracing Wires*. The distance between the wings in a biplane is known as the *Gap*. In many machines the wings are *Staggered*, that is to say, the upper wing is not exactly above the lower but is set either rather in front—*positive Stagger*,—or somewhat behind—*negative Stagger*.

The body of the machine is elongated in form and consists of a light rigid framework of "fair" shape, externally covered in with three-ply wood, canvas, or thin sheet metal to reduce resistance.

The central portion of the body contains the *Pilot's Cockpit*, in which are placed his apparatus for controlling the aeroplane and his instruments.

Behind this is the space for cargo or passengers.

In a single-engined *Tractor Machine* the propelling mechanism—the *Engine* and *Airscrew*—is placed in front of the pilot.

In a twin-engine machine the engines are mounted between the wings on either side of the body.

In a *Pusher Machine* the engine is behind the pilot and the propeller rotates behind the wings.

The lower members of the body framework, known as the *Longerons*, are prolonged forward, and to them the engine is secured.

The framework of the body, known as the *Fuselage*, is prolonged backwards behind the wings and terminates in the *Tail*, a small secondary wing with its length parallel to that of the wings and its chord inclined at a small angle to the chord of the wings.

The *Fin* is fixed in a fore-and-aft vertical plane above the tail. The tail and the fin serve to maintain a steady direction of motion; the tail checks oscillations in the vertical plane — pitching — while the fin is effective in damping out the tendency to turn to right or left.

The machine is carried on the *Landing Chassis*, a stout under-carriage on wheels, mounted on springs so as to absorb the shock on striking the ground when landing.

When taxying at starting the tail rests on the *Tail Skid* until a speed has been reached sufficient to raise it off the ground. The *Wing Skids* are fixed under the wings and prevent the wing tips from striking the ground.

The machine is controlled by the pilot by means of the *Elevator*, the *Rudder*, and the *Ailerons* or *Wing Flaps*.

The rear portion of the tail is hinged about a horizontal axis parallel to the edges of the wings and forms the *Elevator*; on raising the elevator the lift on the tail is reduced and the nose of the machine rises; on depressing the elevator the reverse happens.

The *Rudder* similarly is formed by hinging the rear portion of the vertical fin and serves to guide the horizontal motions of the aircraft.

The *Ailerons* or *Wing Flaps* are portions of the trailing edges of the wings near the tips; these are hinged about axes parallel to the edge and can be raised or lowered by the pilot.

On raising an aileron the lift on the corresponding wing is reduced and the wing depressed.

The control surfaces are connected by control wires to the pilot's cabin; those from the elevator and the ailerons being attached to the *Control Stick*—the *Joy Stick*—while the rudder wires are led to the *Rudder Bar*, which is moved by the feet.

The control stick is fitted with a universal joint at its base. Motion backwards and forwards, parallel, that is, to the length of the machine, moves the elevator; motion to right and left affects the ailerons.

If the control column be pulled back the elevator is raised, causing the nose of the machine to rise.

When the control column is moved to the right the connections are such that the right aileron is raised; this reduces the lift and leads to a depression of the right wing. The same motion depresses the left aileron and raises the left wing; thus a rolling movement is produced.

If the rudder bar be pushed forward by the right foot the rudder moves to the right, causing the machine to turn in the same direction.

Tanks are fitted in suitable positions to contain the petrol and the oil needed for lubrication. For the petrol supply a simple gravity feed, where it can be obtained, is desirable; the tanks should be placed so as to reduce as far as possible the risks from fire; in a single-engined machine positions just below the upper wing and at some distance from the engine are to be recommended, while all the cocks controlling the flow should be readily accessible to the pilot.

AEROPLANE RIBS, DESIGN OF. See "Aeroplane Structures, Theory," § (13).

AEROPLANE STRUCTURES, EXPERIMENTAL TESTS OF STRENGTH

§ (1) INTRODUCTORY. — In most structures, whether of simple or complex design, there are certain parts where the stresses or the distribution of stress are to some extent matters of conjecture. In bridge building and allied branches of engineering, where the weight of the structure is not usually of primary importance, it is possible to provide by liberality in design against failure in such parts. In aircraft design, however, where every pound added to the structure reduces the carrying capacity by the same amount, the strength of parts which are not easily subject to accurate calculation is frequently a matter of doubt, and this doubt can only be removed by the dangerous method of long trial in actual service, or by the safer (and in some cases more convincing) method of laboratory testing.

It is seldom possible accurately to represent the assumed distribution of air load by means of a static test, and a certain amount of compromise becomes necessary.

Accurate representation, however, is of doubtful advantage in cases where the correctness of the assumed loading is uncertain, and in these cases the attainment of accuracy does not warrant the outlay of much time or money.

It is evident that when a supporting surface distorts appreciably, the distribution of the air forces on it will undergo modification. This change cannot easily be represented in the loading during test owing to the complication which would be introduced, and the value of the ultimate load which the test gives may be less but is usually greater than that which might be expected under flight conditions.

Other sources of error in static tests are due to time effect, which is serious only in the case of timber, and to the absence of vibration which may in some tests produce a considerable effect.

In static testing, large loads are generally employed, and it not infrequently happens that, owing to distortion or failure of the structure under test, the stability of the load becomes doubtful and considerable danger may be incurred during examination, measurement, or further loading of the structure. It is an essential part of the arrangement for any test, to ensure against complete collapse of the structure, which prevents examination of the failure in its early stages and may lead to erroneous conclusions. When large concentrated loads are needed in a test it is frequently possible, and always advisable, to keep them as near ground level as conditions will allow.

§ (2) TEST OF MAIN PLANES. — The test of main planes in its most complete form is to some extent a test of the fuselage also. Four types of loading are usually represented.

(i.) *Normal Flight at Stalling Incidence.*— In this case the angle of 16 degrees is usually adopted as the average stalling angle for biplane wings of most modern sections. The centre of pressure is well forward (about 0·28 of the chord from the leading edge).

(ii.) *Normal Flight at High Speed.*—The centre of pressure is further back; about 0·45 to 0·5 of the chord. This usually represents an angle of incidence of about +1° and a lift coefficient of about 0·1 to 0·15.

In both the above cases a drag force is presumed to act on the planes equal to one-seventh of the lift force.

(iii.) *Vertical Nose-dive at Limiting Velocity.* —The planes are at a small negative angle of incidence; the life coefficient is still positive but of very small value. The distribution of the loading causes a "down load" on the front spar, and an "up load" on the rear spar. The moment acting on the planes is balanced by a "down load" on the tail plane. An arbitrary proportion of the weight of the whole machine is assumed to be taken by drag on the main plane structure.

(iv.) *Down Load*, which may occur momentarily due to gusts, etc., or may be of considerable duration in aerobatics.

§ (3) METHOD OF TEST—SUITABLE FOR (i.), (ii.), AND (iv.) OF § (2).—The resultant pressure of the air on the planes is represented by the weight of a distributed load of shot bags. Since the weight acts always in a vertical direction, it is necessary to mount the machine at a suitable angle. The resultant air force does not act in the same direction at all parts of the main planes, so the average direction only can be represented.

The shot bags are spaced to secure a suitable distribution along the span of the planes, and are placed at various distances from the leading edge in accordance with the centre of pressure coefficient at each position.

The ordinary ribs are not under load and must therefore be tested separately. The distribution of load and stresses is, however, fairly correct for the spars, struts, drag struts, internal and main bracing, etc. Since the presence of new fabric usually is sufficient to prevent lateral failure of the main plane spars, and since the stiffening effect of slack fabric (which might occur in service) is a somewhat unknown factor, the test is made with all fabric removed from the planes. To support the shot bags, loose boards are

laid across the front and rear spars. The friction between these boards and the spars tends slightly to restrain the lateral bowing of the latter, but this effect can be set against the restraint which would undoubtedly be supplied by even the slackest fabric which might occur in practice.

This method of loading permits of comparatively free access to the main plane framework for inspection or measurement during test. The weight of the boards and of the planes themselves is included as part of the total test load. A slight error is involved because the distribution of this weight is not quite the same as that adopted for the shot bags, but since the weight of the main plane structure and the boards is usually only 3 per cent to 5 per cent of the total load at the time of failure, the error in distribution is of small magnitude. It is possible, however, to obtain correct distribution (should it be desired for accurate research work) by suitably proportioning the boards or by applying a suitably distributed initial load.

The main plane structure is attached to the fuselage (or boat hull, etc.), and supports are placed under the latter, the reactions at the supports being arranged to represent the weight of the fuselage and its contents. The machine should be mounted at such an angle that the resultant of the assumed "lift" and "drag" forces on the planes will act vertically downwards. The flexibility of the fuselage will affect the distribution of load in the various attachments of the main plane structure. In order to retain the normal flexibility, the fuselage is usually mounted on blocks placed approximately under the principal weights and resting on a system of short beams or levers which finally rock on one transverse beam placed under the position of the centre of gravity of the machine (less main planes).

The couple usually required for equilibrium is supplied by anchoring cables applied to the tail of the fuselage. The reactions in these cables will represent balancing air forces on the tail plane and elevators.

In the case of machines which carry engines, bombs, or other large concentrated loads in the main plane structure, partial support should be supplied at the position of each load to represent the weight of the latter. The correct proportion of the supporting reactions can be ensured by a suitable system of beams or levers. The mounting for tests (i.), (ii.), and (iv.) is illustrated diagrammatically in *Figs.* 1, 2, and 3 respectively.

§ (4) Calculation of Loads, etc., for (i.), (ii.), and (iv.).—In normal horizontal flight, the "lift" components of the air forces on the main plane structure must be equal to the weight of the complete machine, less any lift component of the airscrew thrust and of the air forces on the remainder of the machine. In most cases the latter components are of small magnitude in comparison with the weight of the machine, and may without serious error be neglected. The weight of the main plane structure may be regarded as a distributed load on the planes acting in the opposite direction to the "lift," and therefore introducing very little stress into the members of the structure.

For test or design purposes, therefore, the air forces on the planes in the direction normal to the line of flight may be taken equal to the weight of the complete machine less the weight of the main plane structure. In addition there will be a "drag" component parallel to the direction of flight. This is usually assumed to be everywhere $\frac{1}{7}$th of the "lift" force. The resultant will be 1·07 times the assumed lift acting at an angle of $\tan^{-1}\frac{1}{7}$ or 8·13°.

For convenience, however, it is generally assumed that the resultant force acting on the main plane structure is equal to the weight of the machine less the weight of the main plane structure, and acts in a direction 8° to the rear of the normal to the direction of flight.

In calculating the proportion of the total lift force taken by each of the various planes, allowance must be made for (*a*) wing tip effect; (*b*) decreased lift due to openings, attachments, interference, etc.; and (*c*) relative efficiency of the different planes.

This may conveniently be done by estimating first the "effective area" of each plane. For planes which have leading and trailing edges parallel, and which have no considerable openings or interference, the effective area on each side of the machine will be

$$(\text{semi-span} + 0{\cdot}212 \times \text{chord}) \times \text{chord}.$$

This assumes that the distribution of the lift along the span is represented by the curve standardised by the Air Ministry for strength calculations and illustrated in A.C.A. R. and M. 575. The span in this case should be measured to the extreme tip of the plane.

Where openings or gaps occur in any plane, or where the proximity of the fuselage reduces locally the efficiency of part of the plane, the estimated effective area should be reduced correspondingly.

The ratios of the lift forces exerted by the various planes may be represented by the ratios of their "equivalent areas," these latter being obtained by multiplying the effective areas by factors chosen to represent the relative lift per sq. ft. of the various planes.

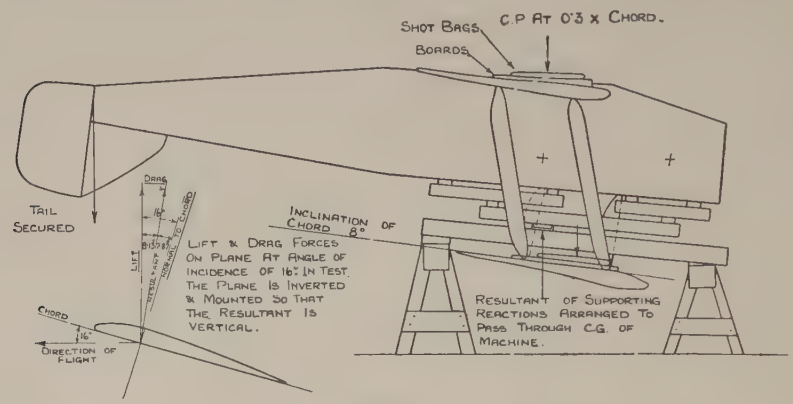

SHOT BAGS
BOARDS
C.P AT 0·3 x CHORD.
TAIL SECURED
DRAG
LIFT
INCLINATION OF CHORD 8°
LIFT & DRAG FORCES ON PLANE AT ANGLE OF INCIDENCE OF 16° IN TEST. THE PLANE IS INVERTED & MOUNTED SO THAT THE RESULTANT IS VERTICAL.
CHORD
16°
DIRECTION OF FLIGHT
RESULTANT OF SUPPORTING REACTIONS ARRANGED TO PASS THROUGH C.G. OF MACHINE.

FIG. 1.

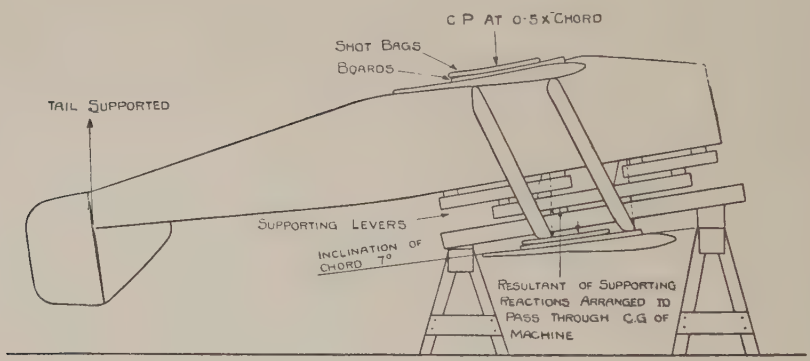

C P AT 0·5 x CHORD
SHOT BAGS
BOARDS
TAIL SUPPORTED
SUPPORTING LEVERS
INCLINATION OF CHORD 7°
RESULTANT OF SUPPORTING REACTIONS ARRANGED TO PASS THROUGH C.G OF MACHINE

FIG. 2.

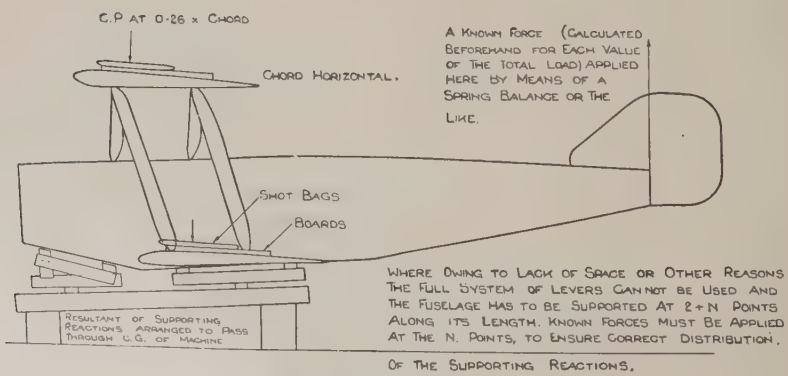

C.P AT 0·26 x CHORD
CHORD HORIZONTAL.
A KNOWN FORCE (CALCULATED BEFOREHAND FOR EACH VALUE OF THE TOTAL LOAD) APPLIED HERE BY MEANS OF A SPRING BALANCE OR THE LIKE.
SHOT BAGS
BOARDS
RESULTANT OF SUPPORTING REACTIONS ARRANGED TO PASS THROUGH C.G. OF MACHINE
WHERE OWING TO LACK OF SPACE OR OTHER REASONS THE FULL SYSTEM OF LEVERS CANNOT BE USED AND THE FUSELAGE HAS TO BE SUPPORTED AT 2+N POINTS ALONG ITS LENGTH. KNOWN FORCES MUST BE APPLIED AT THE N. POINTS, TO ENSURE CORRECT DISTRIBUTION OF THE SUPPORTING REACTIONS.

FIG. 3.

The following ratios are usually assumed to represent the relative lift per unit area of the various planes:

	Monoplane.	Biplane.	Triplane.	Quadruplane.
Top plane .	1·0	1·2	1·2	1·2
Second plane .	..	1·0	0·8	0·8
Third plane .	..	..	1·0	0·8
Lowest plane .	..	..	..	1·0

§ (5) Typical Example.—For a numerical example assume a biplane machine of the following type:

Total weight in flying condition . $W = 5076$ lb.
Weight of main plane structure . $\omega_1 = 890$ lb.
Extreme span of top planes (wing tip to wing tip) . . . . $2L_1 = 46{\cdot}1$ ft.
Extreme span of each bottom plane (wing tip to fuselage) . . . $L_2 = 21{\cdot}17$ ft.
Chord of top planes . . . $c_1 = 5{\cdot}5$ ft.
Chord of bottom planes . . . $c_2 = 5{\cdot}5$ ft.

The effective area of the top planes will be

$$2(L_1 - 0{\cdot}212c_1)c_1 = 2(23{\cdot}05 - 0{\cdot}212 \times 5{\cdot}5) \times 5{\cdot}5 = 241 \text{ sq. ft.}$$

If the fuselage approaches closely to the top planes, or if a portion of the top centre section is removed for any structural reason, a deduction must be made. In the present example it may be assumed that about 15 sq. ft. of the plane are working at a reduced relative efficiency estimated at, say, 60 per cent.

The effective area of the top planes will therefore be

$$241 - 0{\cdot}4 \times 15 = 235 \text{ sq. ft.}$$

The effective area of the bottom planes will be

$$2(L_2 - 0{\cdot}212c_2)c_2 = 2(21{\cdot}17 - 0{\cdot}212 \times 5{\cdot}5) \times 5{\cdot}5 = 220 \text{ sq. ft.}$$

Allowing for the relative efficiencies of the top and bottom planes the "equivalent areas" will be:

Top planes . . $235 \times 1{\cdot}2 = 282$ sq. ft.
Bottom planes . $220 \times 1{\cdot}0 = 220$ sq. ft.

The total normal load on the main plane structure will be

$$W - \omega_1 = 5076 - 890 = 4186 \text{ lb.},$$

where ω_1 is the weight of the main plane structure. This is generally called the "normal weight" of the machine.

If we assume that the machine has been designed for a load factor of, say, 6 for the conditions of flight which are to be represented in test, it will be convenient to arrange the unit of shot loading, so that when the total load (shot + planes + boards) reaches six times the normal weight, the shot load shall then consist of completed layers or units, and the distribution of the whole load shall therefore be correct (according to assumptions).

The total load at a load factor of six will be

$$6(W - \omega_1) = 25{,}000 \text{ lb. (approx.)},$$

and may be expressed $6U + \omega_2$, where U is the unit shot load and ω_2 = the weight of the main planes without fabric or ailerons, but with boards = 1600 lb. Thus

$$U = (W - \omega_1) - \frac{\omega_2}{6} = 3920 \text{ lb.}$$

This unit load is then divided in the ratio of the "equivalent areas" of the planes.

Top planes . . 2200 lb.
Bottom planes . 1720 lb.

Since the shot bags used for loading weigh 25 lb. each, it is convenient to take the nearest even multiple of 50 lb. for the unit load on each plane.

The span of each plane may then be divided into such a number of parts that 50 lb. placed in each will give the unit load on the plane.

Top planes . . 2200 lb. or 44 divisions of 50 lb. each.
Bottom planes . 1700 lb. (say) or 34 divisions of 50 lb. each.

The distribution of the load along the span will, of course, determine the relative length of the various divisions. (As mentioned above, the distribution is in accordance with the curve standardised by the Air Ministry for strength calculations.)

These divisions may then be marked on the boards by chalk or paint, and unit loading may be obtained by placing two shot bags in each division. The assumed centre of pressure is also indicated on the boards by a line, and the shot bags are placed symmetrically on this line.

Loading may proceed by units—two shot bags being placed in each division; or by half units—one shot bag only being placed in each division.

It will sometimes be found convenient to place a strip of fabric over the shot bags as each unit is completed. This binds the piles of shot bags together and prevents displacement when the loading, and therefore the number of layers, becomes large.

During loading, reasonable care is taken to prevent shocks, but the additional stresses

caused by careless placing of a single shot bag are usually so small compared with the stresses due to the total load that it is unnecessary to employ other than unskilled labour for loading. The marking of the boards and the use of fabric strips enables any mistakes made in loading to be detected immediately.

It is, however, important to prevent swaying of the loaded structure. This is apt to occur and can be restrained by assistants stationed at the wing tips, or by suitable dash pots consisting of oil drums, secured to the floor, with pistons connected to the planes near the outer struts.

Suitable staging must be erected to support the staging is mounted on jacks.[1] The planes are supported during loading, and the jacks released after each increase. This method has the advantage that the time during which the structure is acted on by big stresses is materially reduced, but it is not usually adopted here because—

(i.) It does not provide a steady bed to receive the planes at failure;

(ii.) It is difficult to arrange for all jacks to be operated simultaneously at the correct relative speeds, and it is therefore possible seriously to disturb the distribution of stress in the different members, and to cause failure in some part which is momentarily stressed incorrectly.

FIG. 4.

the loaded structure at the time of collapse, and care must be given to its strength and design, as failure to support the shock load may not only render it impossible to determine the primary point of failure and involve the complete destruction of the machine, but may also involve serious injury to the assistants.

The supporting staging should be arranged with cross members under the planes near the attachments of the struts, the initial clearances being graduated to suit the estimated maximum displacements which the parts are likely to experience during the test. The clearances are then reduced to about 0·5 inch by means of loose blocks of wood of thickness so graduated as to allow of adjustment by half-inch steps. This system is simple, safe, and works satisfactorily. A typical single-seater machine erected for test (i.) of the main planes is illustrated in *Fig.* 4.

In the United States of America part of

In France the methods employed by the S.T.AÉ.[2] differ considerably from those described above.

§ (6) MEASUREMENTS.—A complete record of the distortion of the structure is impracticable, and the following measurements are therefore usually made.

(i.) *Distortion of Spars in a Vertical Plane.*—Measurements are made of the displacement (in a vertical plane) of points on the spars near the points of support, midway between, and near the tips. These measurements are not usually taken on spars which are in tension. A complete record of the elastic curve of any spar may be made by photographing it before and during loading. If sufficient care is taken to avoid photographic

[1] *Tech. Notes*, No. 6, Nat. Advisory Committee for Aeronautics, Washington, July 1920.

[2] "Note sur les essais statiques des avions," Capitaine Toussaint, Service Général des Avions, Paris.

errors, the shape of the spar can be obtained from measurements on the developed plates. This method, however, is elaborate, and usually level readings are taken on a vertical scale or staff (held by an assistant), with its lower end resting successively on the various points where displacement is to be measured. Other methods are occasionally adopted, but it is generally inadvisable to use any method which involves the attachment of apparatus to the structure in positions where it could be disturbed by an accidental contact during loading.

(ii.) *Horizontal Movement of the Outer Ends of the Planes.*—This is usually measured by means of plumb lines, the movement being read on horizontal scales. The plumb-bobs may be damped by suspension in oil or water. Measurements (i.) and (ii.) enable changes in stagger or incidence to be calculated.

(iii.) *Lateral Bowing of the Struts.*—Measured midway along the strut.

(iv.) Special measurements are taken in special cases where the deformation or displacement is of particular interest.

§ (7) Method of Test for Nose-dive Conditions, (iii.),[1] § (2).—The resultant air forces on the main planes may be resolved into a couple and a force having "lift" and "drag" components. For the purposes of test the couple and lift force may be represented by suitable upward forces applied to the rear spars and downward forces applied to the front spars. The method of calculating the forces will depend on the data which are available for the particular machine. For general cases, a sufficiently close approximation may be made by calculating the down load on the tail plane from the following formula:

$$P = \frac{KWc}{l},$$

where P = balancing down load on tail plane,
W = weight of complete machine,
c = chord of equivalent plane,
l = distance from centre of gravity of aeroplane to line of action of force on tail plane,
K = constant for wing section = approx. 1 for R.A.F. 14, and 0·6 for R.A.F. 15.

Assuming that the air force on the fuselage has a negligible component normal to the flight path, the resultant lift force on the planes will be equal to the down load on the tail plane, and the moment of the forces on the planes measured about any arbitrary point (say the leading edge of the "equivalent plane") will be equal to the moment of the tail plane force.

For approximate calculations it may be assumed that both lift forces and moments are divided between the main planes in proportion to the "equivalent areas" of the latter (calculated as described in § (5)).

The loads on the front and rear spars of any planes (say, the top planes) may then be calculated as follows:

Down load on top front spars $= F_1 = (l_1/a - 1)P_1$,
and up load on top rear spars $= F_2 = F_1 + P_1$,

where a = distance between top spars,
l_1 = distance from top front spar to line of action of force on tail plane,
P_1 = lift force on top planes.

At limiting velocity the drag force on the whole machine will equal the total weight. Since the weight of the main planes will be distributed in much the same way as the drag of the main planes, it will introduce no stresses in the main plane structure and may conveniently be neglected. The actual drag load which must be supplied by the main plane structure will be the unbalanced portion of the weight of the fuselage, under-carriage, etc., *i.e.* the difference between the weight and drag of these parts.

For test purposes it is probably sufficiently accurate to assume that this drag force on the main planes is distributed along the span in the same way as the lift force.

This somewhat complicated system of forces may be represented by several different test arrangements, but the following is perhaps the simplest.

The machine (complete structurally) is inverted and mounted with the chord of the planes at an angle equal to the angle of incidence during the dive. It is supported at the front spars of all planes. The reactions of these supports represent the "down" loads on the front spars and should be distributed in the assumed manner by the use of a suitable system of levers. A distributed load is applied to the rear spars. This represents the "up" load on these spars. A convenient method of applying this load is to suspend from each spar a flexible platform by means of slings spaced, say, at the rib connections. A shot bag load, distributed in the assumed manner, may then be applied to the platform.

The rear spar of the tail plane may be suspended by a sling arranged initially (and adjusted during test) so as to be vertical, *i.e.* normal to the supposed direction of the flight path. The reaction in this sling will automatically represent the "down" load on the tail plane, provided that the other forces are correctly applied and distributed. The unbalanced gravitational force on the fuselage,

[1] A description of an actual test is contained in *Advisory Committee for Aeronautics, Reports and Memoranda*, No. 588.

etc., may be represented by tension in a horizontal cable attached to a suitable point in the fuselage.

By means of this cable the fuselage should be pulled forward until the suspended links at the front spars make, with the vertical, such an angle that the components of reaction representing drag and "down" load are in the correct ratio.

This assumes, of course, that all the drag acts on the front spar.

In order to prevent the weight of the parts under test affecting the distribution of the forces and reactions, a cable may be attached to a suitable point in the fuselage, and by means of a spring balance, etc., a tension, equal to the weight of the parts in question, may be kept in this cable during the test.

of estimating the tensions of the various weft and warp threads in the loaded fabric.

A static test will give for the ultimate strength of a rib a figure which probably represents with reasonable accuracy the load which the rib will support under flight conditions.

The following method of test involves assumptions for the solution of (iii.) above, but the end load (ii.) is actually applied by covering the test section of plane with fabric.

A number of ribs, usually two, are mounted on dummy (or actual) spars together with stiff wood end ribs of similar outline. All are spaced apart at the normal rib spacing. Short lengths of leading edge, trailing edge, etc., are added to complete a representative section of plane.

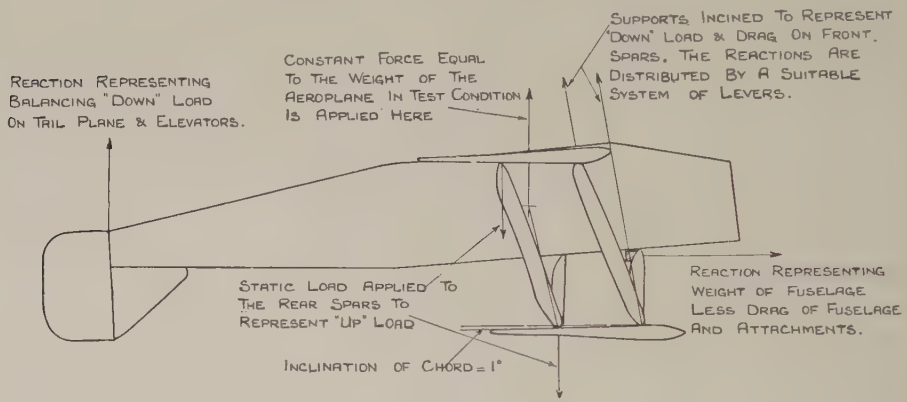

Supports Inclined To Represent "Down" Load & Drag On Front Spars. The Reactions Are Distributed By A Suitable System Of Levers.
Constant Force Equal To The Weight Of The Aeroplane In Test Condition Is Applied Here
Reaction Representing Balancing "Down" Load On Tail Plane & Elevators.
Reaction Representing Weight Of Fuselage Less Drag Of Fuselage And Attachments.
Static Load Applied To The Rear Spars To Represent "Up" Load
Inclination Of Chord = 1°

Fig. 5.

The method of test is illustrated diagrammatically in *Fig.* 5.

Increasing the load in the flexible platforms increases all the reaction forces in the same ratio, and the test may proceed quickly to destruction or as far as may be desired.

§ (8) Test of Main Plane Ribs.—Accurate calculation of the strength of main plane ribs is particularly difficult for three reasons.

(i.) The stiffness of the members and joints in many designs is such that the actual distribution of stress under any particular loading may depart considerably from that calculated on the usual pin joint assumptions. In some cases more refined mathematical processes may overcome this difficulty and yield a closer approximation.

(ii.) The end load due to the initial tension of the fabric is not accurately known.

(iii.) The distribution of load on the rib cannot easily be calculated even when the distribution of air pressure over the surface of the wing is assumed, owing to the difficulty

Special precaution is taken to prevent distortion of the thick end ribs by the tension of the fabric with which the whole section is now covered.

This covering is done in the standard manner, and the initial stresses on the ribs are thus reproduced.

The test is made to represent conditions of flight chosen to stress certain parts with particular severity. Thus flight at stalling incidence involves a heavy up load on the front part of the rib, whereas a nose dive at high velocity produces a "down" load of high intensity on the front part and stresses the rear portion of the rib in the opposite direction. Flight at a small positive angle of incidence stresses the central portion of the rib.

The assumed distributed load on the plane produces alterations in the initial shape and tensions of the fabric, and the load is transferred to the ribs as a distributed load by the weft threads (parallel to the spars), and as a concentrated load by the warp threads *via* the leading edge. This redistribution is

calculated by the aid of certain assumptions,[1] and the final calculated loading is applied to each rib by means of a suitable system of suspended or superimposed (or in large ribs, both) levers. Consideration of the action of the fabric in transferring the air load will show that an increased tension in the warp threads must result, and therefore in the test an increased end load should be applied. This is effected by bands of fabric attached to the leading and trailing edges at each rib and subjected to tension in suitable directions.

During test the section of plane is inverted and supported by the spars. Load is applied to a single platform, and is distributed in the correct ratio to the fabric bands and lever systems by means of suitable levers.

The actual application of distributed load to the ribs will vary according to the method which is adopted for the attachment of the fabric in the final design.

Attention should be given to the static pressure inside the plane. For routine tests this is supposed to be fixed by the position of the vent holes—usually one inch from the trailing edge on the lower surface—but owing to the presence of inspection doors, wounds in the fabric, etc., the pressure in the plane may rise or fall, and the distribution and relative intensity of the forces on the top and bottom fabrics will vary accordingly.

The distortion of the rib during test may conveniently be measured by level readings on a series of scales suspended from the spars and from chosen points on one or both ribs.

§ (9) Detail Tests.—In addition to (and usually preceding) the tests of the main plane structure, certain component parts are frequently subjected to separate tests.

§ (10) Test of Spars.—Spars may be tested by subjecting them to the conditions of loading which are assumed for design.

A distributed load can be applied to the spar by a suitable system of levers, the points of attachment to the spar corresponding (if desired) with the rib positions. The inner end of the spar may be either free or fixed as desired. The spar may be supported by inclined ties so arranged that their reactions will represent, in direction and magnitude, the resultant of the strut and tie wire forces at each point. By adjusting the length of the inclined ties the points of support of the spar may be retained in alignment, or the probable departure from alignment at each loading may be calculated from the dimensions of the complete main plane structure, and during the spar test suitable amounts of non-alignment may be allowed at each stage of the loading.

[1] *Advisory Committee for Aeronautics, Reports and Memoranda*, No. 443.

The lateral bowing of the spar may be restrained by means of horizontal hinged levers (or by vertical slides).

Where the lateral stiffness of a spar is in doubt, the spar may be inclined at such an angle that the ratio of the components of the applied load which act parallel to the two principal axes of the spar section approximates to the ratio of the calculated loads in these two directions.

In this case the spar under test should be restrained by links and bracing members to represent the ribs and internal drag struts and bracing which would be present normally in the actual plane. These members should be attached to a dummy spar having the same value of EI as the actual companion spar, and at each stage of the loading the calculated end load for the latter (actual) spar should be applied to the former (dummy) spar.

If necessary, tests can be made on single bays of spars. In this case the calculated fixing moments must be applied in addition to the simple loading. This method reduces the cost of testing large-sized spars.

The length of spar used for test should in no case be less than the length of the bay, owing to the difficulty of applying the end load with the correct eccentricity at all sections of the spar.

§ (11) Tests of Fittings.—In many cases the strength of detail fittings is not subject to accurate calculation, and where the strength is in doubt tests are of use. The nature of any test will, of course, depend on the type of fitting and the loads to which it is subjected in service. The devising of suitable tests frequently gives scope for the exercise of considerable ingenuity in the application of simple mechanics.

§ (12) Test of Fuselage—Down Load.—Two conditions are usually considered in connection with the testing of fuselages for downward forces on the tail plane.

(i.) *Steep Dives.*—When a large pitching moment and a lift force are applied to the fuselage by the wings and are balanced by a downward air force on the tail plane and elevators. In this case other forces acting on the fuselage have usually little effect on the stresses in the members and may conveniently be neglected for test purposes.

(ii.) *Stalling or Landing.*—When acceleration forces are acting on the engine, tanks, crew, and on the tail unit as more or less concentrated loads, and on the fuselage framework as a distributed load. The tail plane may also be subjected at the same time to a considerable air load.

In test the conditions of (i.) may easily be represented by securing the fuselage at the points of attachment of the main plane structure (due provision being made for the

correct distribution of the reactions) and applying load to the tail plane.

The conditions of (ii.) are more difficult to represent, and it is usual to test the rear part of a fuselage under conditions somewhat similar to (i.) above, and then to test the front part and engine bearers by applying a load at the position of the centre of gravity of the engine, supporting the fuselage centrally and anchoring the tail.

The bracing effect of the crankcase should be represented by a steel plate or other suitable member bolted in position. The nature of the central support will depend on the conditions represented. If the loads are those due to sudden stalls, the fuselage will be supported at the points of attachment of the main plane structure, levers being used to distribute the load, and being so proportioned as to ensure that the resultant of the reactions passes through the centre of pressure of the equivalent chord of the planes. The fuselage should be mounted at the stalling angle which has been assumed.

If the assumed loads are dynamic forces due to landing, the fuselage will be supported at the attachments of the under-carriage, the resultant reaction being arranged to pass through the axle, and the fuselage being mounted with the chord horizontal.

In all cases the tail load is applied conventionally at the hinges of the elevators.

Fabric is usually removed from the fuselage during test. In some designs it is possible that the fabric may restrain the distortion of the longitudinals and enable them to carry a greater end load without failure, but the strengthening effect is generally so uncertain that it is not safe to rely on it for any appreciable increase in the strength of the fuselage as a whole.

During a test the vertical displacements of various points in the framework are measured. The bowing of longitudinals, movements of fittings, etc., are also noted. For accurate work it is advisable either to rig the fuselage beforehand with known tensions in the bracing wires or to note carefully the stages of the loading at which each wire in turn becomes slack.

§ (13) Sideload Test of a Fuselage may conveniently be combined with the test of the rudders and fins, *q.v.*

§ (14) Torsion.—Where the stiffness of a fuselage in torsion is in doubt, a suitable test may be made by securing the fuselage at the points of attachment of the main plane structure, and applying a balanced couple to the tail plane.

§ (15) Monocoque Fuselages.—In general the same method of treatment applies either to monocoque or braced fuselages. The change in the shape of the cross-section should be measured during loading, at various positions along the fuselage.

§ (16) Boat Hulls. — It is occasionally desired to test boat hulls. If the hull carries the tail unit, and flying conditions are to be represented, it may be treated in the same manner as a monocoque fuselage. If "landing" conditions are to be represented some distribution of pressure must be assumed, and may then be represented approximately by a distributed load with suitably placed shot bags. Owing to the doubt which usually exists as to the exact distribution of the actual water pressure, and also on account of the difficulty of reproducing accurately the assumed distribution, these tests are seldom made.

§ (17) Tests of Under-carriage.—Static tests on under-carriages can furnish information on the ultimate load (in the direction of test) which may be supported by the structure, and on the energy absorbed and dissipated by the flexible parts.

A convenient method of testing is to invert the fuselage with under-carriage attached, and load the ends of the axle to represent the reactions of the wheels.

Since wheels and tyres are standard and interchangeable, there is no necessity to include them in each test. It is, however, necessary to ensure that the load is applied to the axle in the correct manner. This may be done by suspending the load from fittings which make contact with the axle at the same positions as the bushes of the wheels. By suitable geometrical construction the resultant of the applied load can be made to travel outwards, as the axle bends, to represent the outward travel of the ground reactions on the treads of the tyres due to the inclination of the wheels during landing.

At intervals during the test readings are taken of the distortion or displacement of the various parts of the under-carriage, and from these the energy absorbed for any load can be calculated. The characteristics for the complete under-carriage can be obtained by adding the energy absorbed by the tyres, which either is known or may form the subject of separate experiment.

By taking measurements during removal of the load, for various values of the latter, the energy dissipated may also be calculated.

It must be noted that these results may strictly be applied to the under-carriage when subject to slow loading only. It is evident that the energy absorbed by a fluid-controlled (Oleo type) under-carriage will depend entirely on the rate of loading, and its action under service conditions cannot be calculated from the results of slow static tests. There is at present inadequate information as to the correction which should be applied to under-

carriages using rubber shock absorbers, but the approximation obtained by assuming that the absorbed energy will be the same for static and dynamic loading will be sufficiently close for general purposes.

When desired, dynamic tests can be made by mounting the under-carriage and wheels under a loaded platform and dropping the whole from various heights. In this case self-recording apparatus must be used to measure the deflections, etc., of the various parts.

§ (18) Test of Ailerons and Elevators.—Owing to the meagre data available as to the distribution of air forces on controlling surfaces, the tests on these parts are usually of a simple character, and aim rather at checking the strength of the fittings and controls than at reproducing any particular conditions which occur in flight.

The surfaces are usually loaded uniformly in the direction of the span (with reduction of the loading near the ends) and with the centre of pressure everywhere one-third of the distance from the front to the rear of the surface. The parts are held in position by means of their control cables, the pilot's control column being secured by a spring balance arranged to read the force which the pilot's hand would have to exert to hold the load.

Ailerons are usually tested under conditions of up load on one side only of the machine, and elevators under conditions of down load.

§ (19) Side Loads on Rudders and Fins.—The fuselage is mounted on its side, and may be supported at the attachments of the planes or at some point which is selected as the probable instantaneous centre of rotation for yaw. Shot bag loading is applied to the fin and rudder. It is usual to distribute the load uniformly on the fin, but on the rudder the centre of pressure is taken to be everywhere one-third of the distance from the front to the rear edge. The total loads on the fin and rudder bear the same ratio as the respective areas. Where the machine has more than one fin or rudder, the total loads on all parts will be in the ratio of the respective areas.

The rudder should be held in position by means of the controls, the rudder bar being held by means of a spring balance which will indicate the pressure which the pilot's foot will have to exert to hold the rudder in position.

During loading the deflection and distortion of the fuselage are measured. Special note is made of any slackening of the "bulkhead" cross-bracing wires which may occur. The change in angle of the rudder should also be noted, because in certain machines the maximum rudder moment which can be brought into play at any particular speed is decided, not by the maximum pressure which can be exerted by the pilot's foot, but by the stretch of the rudder controls.

W. D. D.

AEROPLANE STRUCTURES, THEORY OF

Analysis of Stress Distribution

§ (1) Introduction.—In all aeronautical work one of the foremost problems the designer has to face is lightness of construction consistent with strength requirements; thus, to effect as great economy as possible in dead weight, accurate analysis of the forces brought into play and of their effects becomes essential. The theory of design of aircraft, in fact, may be said to start where that of ordinary structural design finishes. The methods used in the latter, even when special economy is being exercised, become the rule-of-thumb methods of aeronautics. It is not meant to depreciate the value of the less accurate analysis, since it is usually from this as a starting-point that the general design evolves; but present-day design calls for a more exact calculation in order to show where and how modification or saving can be effected without materially weakening the structure or part. Space does not permit of an elaborate discussion of all the problems that present themselves, so attention will be focussed in this article only upon the general principles underlying the methods usually employed for stress calculation in aeroplane frameworks.

The framework which supplies the strength to the aeroplane may be treated in two principal parts: (*a*) the body or fuselage, containing the engine, etc., and about which the machine as a whole is built up; and (*b*) the wings, which in the main supply the sustaining force. The usual method of construction for these is the cross-braced Warren or N type of girder; that is, main booms are taken the whole length of the structure and connected together by struts, the spaces between the struts being cross-braced by wires running diagonally.

§ (2) The Fuselage Framework.—It is usual for the fuselage to be rectangular at sections formed by planes perpendicular to its axis. Four booms or longerons, $abc \ldots$, $a'b'c' \ldots$, $a_1b_1c_1 \ldots$, $a_1'b_1'c_1' \ldots$ (*Fig.* 1), run along the length of the body at the corners of the sections, and are connected by struts cc_1, c_1c_1', $c_1'c'$, $c'c$, the spaces between the struts being cross-braced by wires as at m_1k_1', k_1m_1', and also at the bulkheads bb_1', $b'b_1$, etc. In order to give a faired form to the fuselage, and to reduce the aerodynamic resistance of the machine, the struts in general decrease in

length from the front m to the tail at a, and the whole is completely enclosed in fabric. For the purpose of calculation the front portion mk, which contains the engine frame and also to which the wings are connected, may be regarded as fixed, the fuselage be-

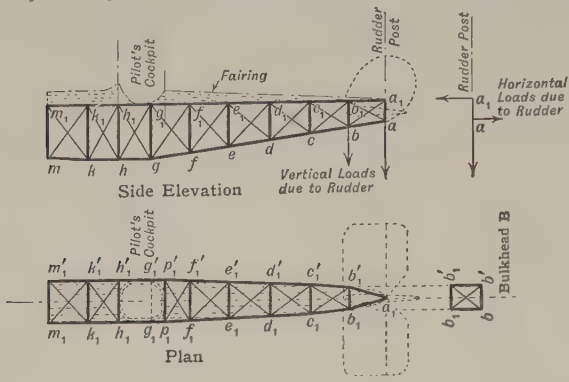


FIG. 1.

coming in effect a cantilever. The load is applied at the end a through the tail plane and rudder. The former produces a force acting along aa_1 and the latter a couple tending to twist the fuselage about its axis. This couple can be replaced by two forces perpendicular to the plane of symmetry of the fuselage and acting through the two points a and a_1.

The magnitude of these forces must be obtained from a knowledge of the aerodynamic properties of the tail system when acting under the most adverse conditions, such as, for example, during looping when the down load on the tail is very large.

§ (3) THE WING STRUCTURE.—The members that exist for constructional purposes in the wing structure cannot in all cases be shielded from the wind as in the case of the fuselage, with the result that aerodynamical considerations frequently enter in to modify the structural design. Attempts have been made to enclose all strength parts of the wing system completely within the wings themselves, but these cases are rare and frequently accompanied by other defects. In the main it is necessary to resort to external bracing, and in the case of biplanes, etc., external struts which, on account of the necessity to fair the section and maintain a low aerodynamic resistance, become far heavier than would normally be the case.

The biplane structure is usually built up from two N girders. One is formed by the two front spars running the whole length of the upper and lower wings, connected together by the gap struts and cross-bracing, the lift wires FB, GC, etc. (*Fig.* 2), and anti-lift wires AG, BH, etc. (*Fig.* 2). The other is composed of the rear spars with the corresponding gap struts and cross-bracing, lift and anti-lift wires. The front spars are usually situated about a quarter to a sixth of the chord length from the leading edges, and the rear spars a third from the trailing edges. In the wings themselves the spars are connected together by ribs and cross-bracing wires (drag wires) (*Fig.* 2), and for final rigidity diagonal bracing is inserted to connect the front spar of the one wing to the rear spar of the other. These bracing wires are called incidence wires (*Fig.* 2).

The gap struts, incidence wires, and lift and anti-lift wires are faired in order to diminish the aerodynamic head resistance.

§ (4) NATURE OF EXTERNAL LOADING ON WINGS DUE TO WIND FORCES.—To determine how the external wind pressure affects the stress in the wing framework, it is necessary to know the law of distribution of the pressure both crosswise along the span and lengthwise in the direction of the chord, for the nature of this distribution will determine which spar, front or rear, and which section of the spar is most heavily stressed for the type of

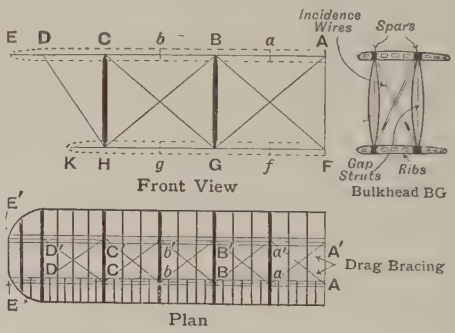


FIG. 2.

flight considered. This distribution can be found by wind-channel experiments. In normal flight the pressure intensity along the span is greatest at mid-span, and falls off almost to zero at the wing tip roughly according to an elliptic law. It will be a sufficiently close approximation to assume that the distribution in load per unit length along the span is constant up to a short distance from the tip. From there onwards it could again be regarded as constant but of smaller amount. This of course only applies to normal flight. In cases where the aeroplane spins rapidly about

a vertical axis the increased forces on the outer wing tips are sometimes so large as to necessitate a considerable increase in strength of certain members.

The ratio between the forces on the front spar to the forces on the rear in the same wing is given roughly by a knowledge of the position of the centre of pressure on that wing. For low angles of attack of the wings—that is, for high speeds in normal flight—the centre of pressure is usually in the neighbourhood of the rear spar, while for high angles of attack it shifts to the vicinity of the front spar.

These remarks only apply to forces normal to the wings. Usually this is all that need be considered, as the effect of the longitudinal force that is the component of the air forces tangential to the chord may be neglected. In the case, however, of a vertical nose-dive to earth at the terminal speed of flight, the normal force becomes small and the longitudinal force is then all-important.

§ (5) The Steps in the Method of Calculating Stresses.—To calculate the stress distribution in such a framework as a wing structure is a matter of considerable difficulty. The final calculation, in fact, can only be worked up to in stages. Many members of the structure are redundant; that is to say, they can be removed without the frame becoming non-rigid as far as the action of the forces under investigation are concerned. The stresses in redundant members unfortunately cannot be found without a complete knowledge of the design of these members. Since, however, the object of the investigation is to furnish us with sufficient information to enable us to calculate the sizes of the parts, we must resort to a method whereby an approximate calculation upon a non-redundant frame will give enough information to enable these parts to be approximately designed. Having then a structure of known dimensions we can introduce the redundancies, and by successive approximations arrive at an accurate estimate of the stress distribution. In the wings the principal redundancies are the incidence wires and the continuity of the spars at the junctions with the gap struts.

§ (6) Approximate Estimate of Forces in Wing Members.—The first step in the calculation must be to construct a simple line diagram of the frame with all redundancies removed. Thus we may remove the incidence wires and suppose that instead of the spars being continuous they are pin-jointed to the gap struts forming a simple pin-jointed frame. Neglecting the longitudinal forces on the wings and also the stagger, we can suppose the whole of the load to be taken up by the front and rear girders already mentioned; the amount borne by each will depend roughly upon the position of the centre of pressure on each wing. One-half of such a girder is shown diagrammatically in *Fig.* 3. The loads, acting on the overhangs ED and KH,

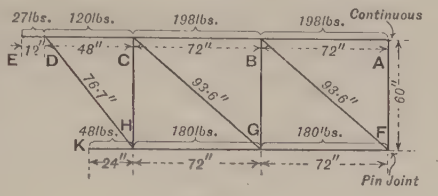


Fig. 3.

in this case of 27 lbs. and 48 lbs., may be supposed to act at D and H respectively, and the load on any span such as CB may be regarded as acting half at C and the other half at B. Treating the structure as a pin-jointed frame the direct forces in the members can be found by simple resolution or by Bow's method. The magnitude and nature of these are given in *Fig.* 4, where the minus sign indicates compression, and from a knowledge of these the gap struts and bracing wires can at once be designed.

Before the spars can be designed, however, it is necessary to determine the bending

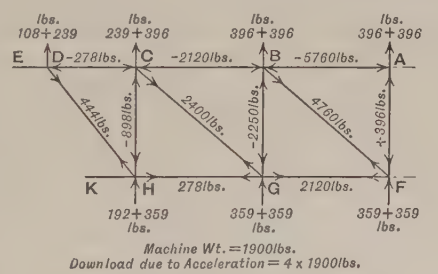


Fig. 4.

moments they are called upon to withstand. For this purpose we will require a few beam theorems, which will now be discussed.

§ (7) Fundamental Equation used in Beam Theory.—It is desirable to extend the ordinary beam formulae to the case of small deflections of straight beams under end thrust as well as under lateral load. Attention will be confined to flexure in the plane of symmetry of the beam, in which plane the lateral load will be supposed to act.

Let the axes of reference be OX, OY (*Fig.* 5), where OX is along the axis of the unloaded beam and OY at right angles to it.

The following symbols will be used with reference to an element of the beam of length δx, deflections

and forces being positive when acting as in *Figs.* 5, 6, and 7:

x=abscissa in inches of any section of the beam measured from OY.

y=deflection in inches of the neutral axis of that section measured vertically upwards from OX.

θ=slope of beam in radians.

w=lateral load in lbs. per inch run.

F=end thrust in lbs.

=force normal to a cross-section at x taken parallel to OY.

f=shear in lbs. across this section.

T=thrust in lbs. normal to a cross-section at x when perpendicular to longitudinal neutral axis,

=F approximately.

S=shear in lbs. across this section.

M=bending moment in lb. inches on section $b'c'$.

EI=flexural rigidity of beam at x in lbs.×sq. inches.

A=area of beam in square inches at x.

R=radius of curvature of neutral axis in inches.

The forces and moments indicated in the diagrams are exerted by the rest of the beam upon the element under consideration.

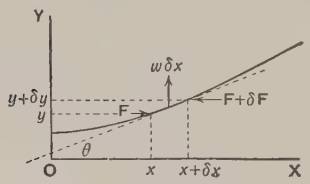


FIG. 5.

It can easily be shown that:

(1) From *Fig.* 6, by resolving forces on the element vertically,

$$w=-\frac{df}{dx}. \quad . \quad . \quad . \quad (1)$$

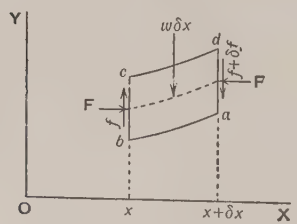


FIG. 6.

(2) From *Fig.* 7, by taking moments about P,

$$-\frac{dM}{dx}=S. \quad . \quad . \quad . \quad . \quad (2)$$

Hence since

$$S=f\cos\theta-F\sin\theta$$

$$=f-F\frac{dy}{dx} \text{ nearly,}$$

$$\frac{d^2M}{dx^2}=w+\frac{d}{dx}\left(F\frac{dy}{dx}\right) \text{ from (1).} \quad . \quad (3)$$

By finding the extension or compression of elementary layers of the beam taken parallel to

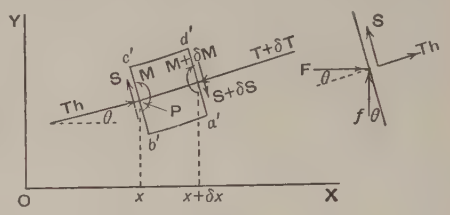


FIG. 7

the neutral plane, and assuming that plane sections remain plane, we find on integrating that

$$(3) \quad M=-\left(E-\frac{F}{A}\right)\frac{I}{R}$$

$$=-EI\frac{d^2y}{dx^2} \text{ approximately,} \quad . \quad (4)$$

since F/A is small compared with E, and the curvature, approximately d^2y/dx^2, is negative when the moment tends to make the beam convex upwards.

The essence of the theory of the flexure of beams is contained in these three equations, and nothing more than these will be utilised in the present development of the work. The most convenient form of differential equation for the deflection y of the beam is obtained directly by inserting the expression found for M in (4) into equation (3), thus obtaining

$$\frac{d^2}{dx^2}\left(EI\frac{d^2y}{dx^2}\right)+\frac{d}{dx}\left(F\frac{dy}{dx}\right)+w=0, \quad . \quad (5)$$

or, since for the present we need only confine our attention to those cases where F and EI are constant,

$$EI\frac{d^4y}{dx^4}+F\frac{d^2y}{dx^2}+w=0. \quad . \quad . \quad (6)$$

It will be noticed that the equation is of the fourth order, whereas it is usually given in the second order. The former can be obtained from the latter by differentiating twice, but equation (6) is in a form most suitable for directly inserting any type of end condition.

The solution of (6), when w represents uniform lateral loading, is

$$y=A\sin\lambda x+B\cos\lambda x+Cx+D-\frac{wx^2}{2F}, \quad (7)$$

where $$\lambda^2=\frac{F}{EI},$$

and A, B, C, and D can be determined if four conditions at the ends are known. This solution can easily be verified by differentiation and by substitution in (6).

§ (8) THEOREM OF THREE MOMENTS.[1]—Suppose ABC (*Fig.* 8) to represent a part of a loaded beam resting on a number of supports

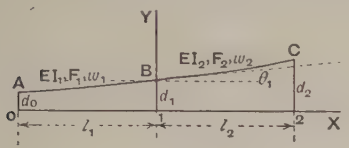


FIG. 8.

of which three are indicated (A, B, and C). It will be justifiable to discuss the effect of the loading by concentrating attention on any portion of the beam provided the effect of the remainder of the beam on that portion is replaced by an equivalent shear and bending moment at the ends of the portion considered. It is proposed accordingly to find the effects of loading a series of separate beams AB, BC, etc., assumed initially unconnected, and then to make these continuous by the introduction of the requisite end conditions.

Let EI_1 and EI_2 be the flexural rigidities, F_1 and F_2 the end thrusts, l_1 and l_2 the lengths, and w_1 and w_2 the lateral loading of the two bays AB and BC respectively. Let d_0, d_1, and d_2 be the deflections, and M_0, M_1, and M_2 the bending moments at A, B, and C respectively.

Along BC we have from (7)

$$y_2=U_2\sin\lambda_2x+V_2\cos\lambda_2x+W_2x+P_2-\frac{w_2x^2}{2F_2}, \quad (8)$$

where $$\lambda_2{}^2=\frac{F_2}{EI_2},$$

and where U_2, V_2, etc., are to be determined from the end conditions.

Using $M=-EI(d^2y/dx^2)$ and the values for the deflections and bending moments at B and C, where $x=0$ and $x=l_2$ respectively, we obtain, when these supports are simple supports, *i.e.* do not exert a moment on the beam,

$$\text{At B}\begin{cases} d_1=V_2+P_2, \\ \dfrac{M_1}{EI_2}=V_2\lambda_2{}^2+\dfrac{w_2}{F_2}, \end{cases}$$

$$\text{At C}\begin{cases} d_2=U_2\sin\phi_2+V_2\cos\phi_2+W_2l_2+P_2-\dfrac{w_2l_2{}^2}{2F_2}, \\ \dfrac{M_2}{EI_2}=\lambda_2{}^2(U_2\sin\phi_2+V_2\cos\phi_2)+\dfrac{w_2}{F_2}, \end{cases}$$

[1] Report to Advisory Committee for Aeronautics, R. and M. 364, "Critical Loading of Struts and Structures," Part I., by W. L. Cowley and H. Levy.

where $\phi_2=\lambda_2l_2$;

$$\therefore V_2=\frac{M_1l_2{}^2}{EI_2}\frac{1}{\phi^2}-\frac{w_2l_2{}^4}{\phi_2{}^4EI_2}, \quad . \quad (9)$$

$$P_2=d_1-\frac{M_1}{EI_2}\frac{l_2{}^2}{\phi_2{}^2}+\frac{w_2l_2{}^4}{\phi_2{}^4EI_2}, \quad . \quad (10)$$

$$W_2=\frac{d_2-d_1}{l_2}+\frac{w_2l_2{}^2}{2\phi_2{}^2EI_2}+\frac{1}{\phi_2{}^2}\left(M_1-M_2\right)\frac{l_2}{EI_2}, \quad (11)$$

$$U_2=\frac{1}{\phi_2{}^2\sin\phi_2}\left\{M_2-M_1\cos\phi_2 -\frac{w_2l_2{}^2}{\phi_2{}^2}(1-\cos\phi_2)\right\}\frac{l_2{}^2}{EI_2}. \quad (12)$$

Now the slope θ at B where $x=0$ in the beam BC, is

$$\theta_1=\left(\frac{dy_2}{dx}\right)_{x=0}=\lambda_2U_2+W_2$$

$$=\frac{1}{\phi_2\sin\phi_2}\left\{M_2-M_1\cos\phi_2 -\frac{w_2l_2{}^2}{\phi_2{}^2}(1-\cos\phi_2)\right\}\frac{l_2}{EI_2}$$

$$+\frac{d_2-d_1}{l_2}+\frac{w_2}{2\phi_2{}^2}\frac{l_2{}^3}{EI_2}+\frac{1}{\phi_2{}^2}\left\{M_1-M_2\right\}\frac{l_2}{EI_2}$$

$$=\frac{M_1l_2}{EI_2}\left(1-\frac{\phi_2}{\tan\phi_2}\right)\frac{1}{\phi_2{}^2}+\frac{M_2l_2}{EI_2}\left(\frac{\phi_2}{\sin\phi_2}-1\right)\frac{1}{\phi_2{}^2}$$

$$-\frac{d_1}{l_2}+\frac{d_2}{l_2}-\frac{w_2l_2{}^3}{2EI_2}\left[\frac{\tan\phi_2/2}{\phi_2/2}-1\right]\frac{1}{\phi_2{}^2}. \quad . \quad (13)$$

Similarly the slope at B where $x=l_1$ in the bay AB is

$$\theta_1=\frac{M_0l_1}{EI_1}\left(\frac{\phi_1}{\sin\phi_1}-1\right)\frac{1}{\phi_1{}^2}-\frac{M_1l_1}{EI_1}\left(1-\frac{\phi_1}{\tan\phi_1}\right)\frac{1}{\phi_1{}^2}$$

$$-\frac{d_0}{l_1}+\frac{d_1}{l_1}-\frac{w_1l_1{}^3}{2EI_1}\left[\frac{\tan\phi_1/2}{\phi_1/2}-1\right]\frac{1}{\phi_1{}^2}. \quad (14)$$

Equating these two quantities we obtain

$$M_0A_1+M_1(B_1+B_2)+M_2A_2$$

$$=-\frac{d_0}{l_1}+d_1\left(\frac{1}{l_1}+\frac{1}{l_2}\right)+\frac{d_2}{l_2}-K_1-K_2, \quad (15)$$

where $$A=\frac{l}{EI}\frac{1}{\phi^2}\left(\frac{\phi}{\sin\phi}-1\right)=\frac{l}{EI}\cdot\alpha,$$

$$B=\frac{l}{EI}\frac{1}{\phi^2}\left(1-\frac{\tan\phi}{\phi}\right)=\frac{l}{EI}\cdot\beta,$$

$$K=\frac{wl^3}{2EI}\frac{1}{\phi^2}\left[\frac{\tan\phi/2}{\phi/2}-1\right]=\frac{wl^3}{2EI}\cdot\gamma.$$

The quantities α, β, and γ are given in Table I. for various values of ϕ when F is positive, *i.e.* F represents a compression. When F is negative, *i.e.* F represents a tension, these quantities are written as α', β', and γ' in the table. Generally we may write for the rth and $(r+1)$th bays

$$M_{r-1}A_r + M_r(B_r + B_{r+1}) + M_{r+1}A_{r+1}$$

$$= -\frac{d_{r-1}}{l_r} + d_r\left(\frac{1}{l_r} + \frac{1}{l_{r+1}}\right) - \frac{d_{r+1}}{l_{r+1}} - K_r - K_{r+1}. \quad (16)$$

This provides an equation between the three bending moments at three neighbouring simple supports in terms of the lateral loadings, lengths, flexural rigidities and end thrusts of the two contiguous bays, and the deflections at the supports. When these quantities are known it is a simple matter to determine the bending moments at all the supports of such a continuous beam if the bending moments at two, usually the end supports, be known; for by writing down the equation of three moments for each set of three consecutive supports, sufficient simple linear equations are obtained to determine the required quantities.

The bending moments at intermediate points along the bays can then be found at once by differentiating equation (8) twice, and multiplying by $-EI$, inserting the values for U V W, and P given in equations (9), (10), etc., and the values for the bending moments at the supports as already evaluated.

In Table I., near $\phi = \pi$,

$$\alpha = \frac{1}{\pi\theta},$$

$$\beta = \frac{1}{\pi\theta} + \frac{2}{\pi^2},$$

$$\gamma = \frac{1}{\pi^2}\left(\frac{4}{\pi\theta} + \frac{12}{\pi^2} - 1\right),$$

where $\phi = \pi - \theta$.

§ (9) Reaction at the Supports.—Consider (*Fig.* 9) an element of the beam at a support.

Table I

$\phi = l\sqrt{\frac{F}{EI}}$ or $= l\sqrt{\frac{\text{Tens}}{EI}}$.	$\alpha = \frac{1}{\phi^2}\left(\frac{\phi}{\sin\phi} - 1\right)$.	$\beta = \frac{1}{\phi^2}\left(1 - \frac{\phi}{\tan\phi}\right)$.	$\gamma = \frac{1}{\phi^2}\left(\frac{\tan\phi/2}{\phi/2} - 1\right)$.	$\alpha' = \frac{1}{\phi^2}\left(1 - \frac{\phi}{\sinh\phi}\right)$.	$\beta' = \frac{1}{\phi^2}\left(\frac{\phi}{\tanh\phi} - 1\right)$.	$\gamma' = \frac{1}{\phi^2}\left(1 - \frac{\tanh\phi/2}{\phi/2}\right)$.
·0	·167	·333	·0833	·167	·333	·0833
·3	·167	·336	·086	·165	·331	·0826
·6	·175	·343	·088	·160	·325	·0805
·9	·186	·352	·091	·152	·317	·0774
1·2	·200	·367	·097	·142	·305	·0730
1·5	·222	·295	·109	·131	·293	·0679
1·8	·261	·436	·125	·120	·278	·0634
2·1	·323	·501	·148	·108	·264	·0581
2·4	·444	·630	·197	·097	·250	·0531
2·7	·711	·935	·310	·0872	·237	·0481
3·0	..	..	·843	·0777	·224	·0441
3·3	..	..	−·770	·0696	·213	·0401
3·6	−·684	−·484	−·262	·0620	·201	·0366
3·9	−·440	−·209	−·153	·0553	·191	·0333
4·2	−·331	−·075	−·100	·0495	·181	·0305
4·5	−·278	·000	−·071	·0444	·173	·0278
4·8	−·252	+·066	−·060	·0390	·165	·0256
5·1	−·250	+·115	−·051	·0360	·157	·0235

Let f_l be the vertical shear to the left of this element and f_r that to the right. Since this

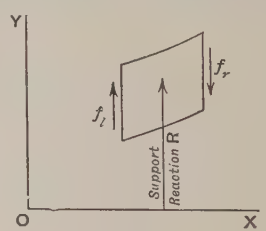


Fig. 9.

element is in equilibrium the reaction R is clearly given by

$$R = f_r - f_l. \quad . \quad . \quad . \quad (17)$$

Taking for example support B (*Fig.* 8), then from (2)

$$f_r = S + F_2 \frac{dy}{dx}, \quad . \quad . \quad . \quad (18)$$

when x is put equal to zero for the second bay BC.

Now $$S = -\frac{dM}{dx} = EI_2 \frac{d^3y}{dx^3},$$

$$\therefore f_r = EI_2 \frac{d^3y}{dx^3} + F_2 \frac{dy}{dx}, \quad . \quad . \quad (19)$$

when $x=0$. From (19) using (8) at $x=0$,

$$f_r = \frac{1}{l_2}\left\{M_1 - M_2 + \frac{w_2 l_2^2}{2} - F_2(d_1 - d_2)\right\}. \quad (20)$$

Similarly for the bay AB

$$f_l = -\frac{1}{l_1}\left\{M_1 - M_0 + \frac{w_1 l_1^2}{2} - F_1(d_1 - d_0)\right\}, \quad (21)$$

giving

$$R_2 = -\frac{1}{l_1}\{M_0 - M_1 - F_1(d_0 - d_1)\} + \frac{w_1 l_1}{2}$$

$$+\frac{1}{l_2}\{M_1 - M_2 - F_2(d_1 - d_2)\} + \frac{w_2 l_2}{2}. \quad (22)$$

But originally (*Fig.* 4) the reaction was taken as $\frac{1}{2}(w_1 l_1 + w_2 l_2)$, and thus one effect of the continuity of the spar, etc., is to increase the upload at the joints by an amount given by

$$\tfrac{1}{2}\{w_1 l_1 + w_2 l_2\} - R_2 = R_2', \text{ say,}$$

$$= \frac{1}{l_1}\left\{M_0 - M_1 - F_1(d_0 - d_1)\right\}$$

$$-\frac{1}{l_2}\left\{M_1 - M_2 - F_2(d_1 - d_2)\right\}. \quad (23)$$

§ (10) Approximate Calculation of Bending Moment Diagram and Design of Spars.—To obtain the approximate dimensions of the spars it will be necessary in the first place to neglect the effect of end thrust and treat each spar separately as a continuous beam. The points of support of the beam are the points of attachment to the gap struts and cross-bracing.[1] The bending moments at the supports can immediately be found by using the form of the equation of three moments for zero end thrust. This is obtained from equation (16) by making ϕ limit to zero giving

$$M_{r-1} l_r + 2M_r(l_r + l_{r+1}) + {}_{r+1}M l_{r+1}$$

$$-\tfrac{1}{4}\{w_r l_r^3 + w_{r+1} l_{r+1}^3\}. \quad (24)$$

[1] Usually the lines of action of the forces in the wires do not meet the neutral axis of the beam at the junction of the struts with that axis. This introduces offset moments, and for a full discussion of the effect of these, reference should be made to R. & M. No. 83, in the Aeronautical Advisory Committee Report, 1912–13.

This equation it will be noticed is independent of the modulus of the cross-section of the beam, whereas (16) is not. To evaluate the bending moments at the supports, this equation must be used on every set of three consecutive supports, such as DCB, CBA, BAB′ and HGF, *Fig.* 3. In the case of support D for the upper spar and B and F for the lower, the bending moments are known and equal to 162 and 576 lb. in. and zero respectively. Solving the three equations for the upper spar and remembering that the bending moment at B′, the support on the other half of the girder symmetrically placed with respect to B, is equal to the bending moment at B, we get

$$M_A = 4620 \text{ lb. in.}$$

$$M_B = 5030 \text{ ,, ,,}$$

$$M_C = 3790 \text{ ,, ,,}$$

The bending moments at other points along the spars can be found by constructing the bending moment diagrams. These are obtained first by constructing the parabolic bending moment diagrams for each bay AB, etc., on the assumption that they are beams simply supported at the ends. If then ordinates be raised at the supports equal in magnitude to the bending moments there and connected by straight lines as in *Fig.* 10,

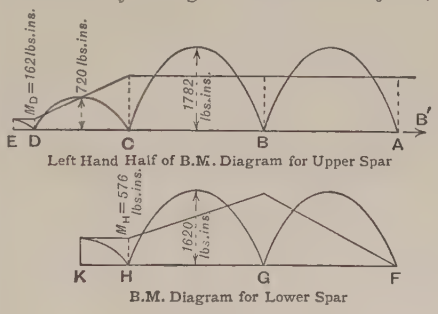

$M_D = 162$ lbs.ins.
720 lbs.ins.
1782 lbs.ins.
E D C B A B′
Left Hand Half of B.M. Diagram for Upper Spar
$M_H = 576$ lbs.ins.
1620 lbs.ins.
K H G F
B.M. Diagram for Lower Spar

Fig. 10.

the bending moment at any position along the spar will be the difference between this and the parabolic diagram. *Fig.* 10 represents the bending moment diagrams for both the upper and the lower spars for *Fig.* 3.

From the knowledge of the bending moments calculated as above, it is now possible to estimate approximately the size of the cross-sections of the spars.

§ (11) Effect of End Thrust upon Bending Moments.—Now that the dimensions of the spars are approximately determined it is possible to make a more accurate calculation of the bending moments. The non-dimensional quantity ϕ can now be calculated and equation (16) utilised. This equation

when written in its most convenient form is, for a uniform spar,

$$M_{r-1}l_r a_r + M_r(l_r\beta_r + l_{r+1}\beta_{r+1}) + M_{r+1}l_{r+1}a_{r+1}$$
$$= EI\left\{-\frac{d_{r+1}}{l_r} + d_r\left(\frac{1}{l_r}+\frac{1}{l_{r+1}}\right) - \frac{d_{r+1}}{l_{r+1}}\right\}$$
$$+ \frac{w_r l_r^3}{2}\gamma_r + \frac{w_{r+1}l_{r+1}^3}{2}\gamma_{r+1}. \quad . \quad . \quad (25)$$

The method of determining the deflections d_r, etc., will be given in a later section.

At intermediate points along the bays the bending moment is obtained from $M = -EId^2y/dx^2$ where y has the form given in equation (8). Using this after the bending moments at the supports have been calculated by equations (25), a more accurate bending moment diagram for this design can be constructed. This diagram to all practical purposes is sufficiently accurate for the final calculations. It will indicate where the original approximate design can be improved, and the modifications if made may be regarded as too small to affect the bending moment diagram any further.

A correction for the effect of the continuity of the spar upon the direct forces in the members of the structure can be made by using equation (23). In the case of a calculation on the girder in *Fig.* 3, the alteration in direct forces was found to be approximately that given in *Fig.* 11,

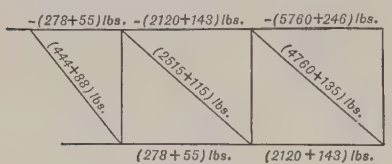


FIG. 11.

where the figures $-(278+55)$ lbs. indicate that the member is in a state of compression of magnitude 278 lbs. in the case of the pin-jointed structure, and $(278+55)$ lbs. when the spars are taken as continuous.

§ (12) STRESS DUE TO BENDING OF SPARS IN PLANE OF WING.—The effect of bending in the plane of the wing can be considered apart from the bending normal to the planes when there is no stagger, and when the effects of the incidence wires are neglected. In this case the most adverse type of loading is obtained when the machine is nose-diving to earth at the terminal speed of flight. The total longitudinal force on the wings will then be equal to the total weight of the machine less the resistance of the body, and may be divided between the wings in the ratio of their lengths after the resistance of the body, etc., has been subtracted.

The structure in the plane of the wing, that is the girder formed by the front and rear spars in the wing, the ribs and cross-bracing, is rather complicated for analysis, but a good enough approximation can be made which will answer practical purposes. The spars, *Fig.* 2, may be supposed simply supported at the positions of the gap struts, ABC, etc., and also where the cross-bracing (drag wires) are attached as at *a*, *b*, etc. The ribs connecting the rear and front spars may be assumed so close together that the deflection of any position of the front spar may be supposed the same as the deflection of the corresponding point on the rear spar immediately behind it. The two ribs may now be regarded as constituting together a continuous beam, the lengths of the bays of which are the same as those in the spars. The moment of inertia of the continuous beam will be the sum of the moments on inertia of the rear and front spars, and the thrust in any one bay the algebraic sum of the thrusts in the two corresponding portions of the spars. The direct forces in the various members can be found by simple resolution of forces (Bow's method) as in the previous case. To do this, it is convenient to assume that the front spar takes all the applied load. Any error in this assumption will only affect the forces in the ribs, BB′, etc., and therefore the question need only be discussed when designing these ribs.

In calculating the dimensions of the spars by this method it will be seen that we only determine the sum of the moments of inertia of the rear and front spars. The way this is divided between the two will depend on the shape of the section; the fact that the two spars are made to deflect together excludes the possibility of determining the division directly.

§ (13) DESIGN OF THE RIBS.—A rib may be regarded as an overhanging beam simply supported at the wing spars, loaded normally over the whole length and under compression between the supports. The total normal load is determined by the total normal force upon that portion of the wing, cut off by the two planes bisecting the spaces between the rib and its two neighbours. The law of distribution of force along the rib can be found from pressure plotting experiments carried out in a wind channel upon a model of the aerofoil.

The thrust in the portion of the ribs between the spars is extremely difficult to calculate. An approximate figure, however, may be found by supposing that the bending of the rear spar in the plane of the wing is brought about by the tensions and compressions in the ribs, the front and rear spars being assumed to bend by the same amount. The maximum compression in the ribs found by this calculation gives a rough figure which, together with the lateral load, should enable us to design these members.

§ (14) Design of Struts.[1]—On account of the necessity of keeping the dead weight of construction and the aerodynamic head resistance as low as possible, it is often advisable to use struts which are not uniform in cross-section. The gap struts, for example, are usually made to taper off towards the ends, so that for the same strength both the head resistance and the weight are less than those of a uniform strut. In practice the draughtsman meets with two distinct types of problems, one to design a strut of a given strength but of minimum weight, and the other to calculate the strength of a given strut not uniform throughout its length. The first problem has been solved by Messrs. Barling and Webb, and reference should be made to their Report to the Advisory Committee for Aeronautics, R. & M. 343.

The second problem arises when the requirements of the strut are not definitely known or are too complicated to receive mathematical interpretation, and when the general outline can be settled by experience or is fixed by other considerations.

In the general problem of the crippling of a strut of any given law of variation in flexural rigidity, the equation to be solved is, putting $w=0$ and F constant in (5),

$$\frac{d^2M}{dx^2}+\frac{F}{EI}M=0, \quad . \quad . \quad (26)$$

where I is some given function of x.

In the drawing office the law of moment of inertia will not generally be specified by means of an analytic expression, but rather in the more convenient form of a curve. The method of solution therefore most suitable for such conditions will evidently be one depending on graphical methods of integration.

Without entering into any proof of the matter the solution of the given equation may be written

$$\begin{aligned} M=A\Big\{1-F\int_0^x dx\int_0^x\frac{dx}{EI} \\ +F^2\int_0^x dx\int_0^x\frac{dx}{EI}\int_0^x dx\int_0^x\frac{dx}{EI}+\ldots\Big\} \\ +B\Big\{x-F\int_0^x dx\int_0^x\frac{xdx}{EI} \\ +F^2\int_0^x dx\int_0^x\frac{dx}{EI}\int_0^x dx\int_0^x\frac{xdx}{EI}+\ldots\Big\}, \quad (27) \end{aligned}$$

where A and B are arbitrary constants and the terms in the two infinite series are each two integrations higher than the preceding one according to a simple law.

We may write this

$$M=AU(x)+BV(x). \quad . \quad . \quad . \quad (28)$$

[1] Report to Advisory Committee for Aeronautics, R. & M. 484, "Critical Loading of Struts and Structures," Part IV., by W. L. Cowley and H. Levy.

A and B are to be obtained from the end conditions, viz.

$$\left.\begin{aligned} x=0,\ M=M_0 \\ x=l,\ M=M_1 \end{aligned}\right\}, \quad . \quad . \quad . \quad (29)$$

where the origin of co-ordinates is now taken at the end of the strut. Hence

$$\left.\begin{aligned} M_0=AU(0)+BV(0) \\ M_1=AU(l)+BV(l) \end{aligned}\right\}. \quad . \quad . \quad (30)$$

When these equations are solved for A and B, it is seen that they have the common denominator

$$U(0)V(l)-V(0)U(l). \quad . \quad . \quad . \quad (31)$$

Crippling will occur when the bending moments become large in comparison with M_0 and M_1, and this demands that the above expression should vanish. Hence

$$U(0)V(l)-V(0)U(l)=0. \quad . \quad . \quad (32)$$

But from the expressions for U and V it is clear that

$$\begin{aligned} U(0)&=1, \\ V(0)&=0. \end{aligned}$$

Hence the condition for crippling becomes

$$V(l)=0, \quad . \quad . \quad . \quad . \quad (33)$$

i.e.

$$\begin{aligned} l-F\int_0^l dx\int_0^x\frac{xdx}{EI} \\ +F^2\int_0^l dx\int_0^x\frac{dx}{EI}\int_0^x dx\int_0^x\frac{xdx}{EI}+, \text{ etc.} \quad (34) \end{aligned}$$

This is an equation containing an infinite number of terms as an equation to solve for F the crippling force.

But the formula is not nearly so formidable as at first sight appears.

In the first place, each of the terms in this expression can be obtained with great rapidity by a simple process involving nothing more than the use of an ordinary planimeter, or the integration of a curve by the mean ordinate method. In the second place, it can be proved that the series is so rapidly convergent that no more than the first few terms, frequently no more in fact than the terms actually given above, need be treated, and the equation may be considered as a quadratic in F, the lowest root being taken.

A first check on the validity of this series may be made by evaluating the expression for the case of a uniform strut, where EI is constant. The series then becomes

$$l-\frac{F}{EI}\int_0^l dx\int_0^x xdx+\frac{F^2}{E^2I^2}\int_0^l dx\int_0^x dx\int_0^x dx\int_0^x xdx, \text{ etc.},$$

i.e.

$$l-\frac{Fl^3}{EI}\cdot\frac{1}{3!}+\frac{F^2l^5}{E^2I}\cdot\frac{1}{5!}\ldots=0,$$

or

$$\phi-\frac{\phi^3}{3!}+\frac{\phi^5}{5!}\ldots=0,$$

after multiplying by $\sqrt{(F/EI)}$, where $\phi=l\sqrt{F/EI}$,

$$\sin\phi=0,$$

i.e. $\phi=\pi$, $\phi=0$ not being a solution.

For convenience in carrying through the graphical integration it is advisable to throw the series obtained into a non-dimensional form. This may be done by transforming it by the substitution

$$X=\frac{x}{l},$$

$I=I_0R$, I_0 being the moment of inertia at one end, and writing

$$\phi^2=\frac{Fl^2}{EI_0},$$

when we obtain

$$1-\phi^2\int_0^1 dX\int_0^X\frac{X\,dX}{R}$$

$$+\phi^2\int_0^1 dX\int_0^X\frac{dX}{R}\int_0^X dX\int_0^X\frac{X\,dX}{R}\ \ldots=0. \quad (35)$$

The non-dimensional quantity ϕ^2 is called the class variable and it will be noted that our solution is a simple power series in ϕ^2.

The graphical process in equation (35) is extremely simple. The curve for X/R is plotted for the range X=0 to X=1, the whole length of the strut, and the value of the integral obtained graphically, by means of a planimeter or by mean ordinates, can then be plotted. This determines $\int_0^X X\,dX/R$, which is once more integrated for the range 0 to 1, and plotted. The value of the ordinate at X=1 determines the first coefficient, viz. $\int_0^1 dX\int_0^X dX/R$. Each ordinate of the last curve is then multiplied by 1/R and integrated twice as before, and the value of the final ordinate at X=1 determines the coefficient of ϕ^4. In some cases it might be found necessary to proceed to higher terms, but if necessary this may be done with equal rapidity by multiplying by 1/R and integrating twice. After a little practice it will be found that by this process, apparently complicated, the strength of a strut can be calculated in a short time. The final equation obtained is in the form

$$1-a\phi^2+b\phi^4\ \ldots\ =0,$$

which, when solved for ϕ^2 and the lowest positive root selected, gives the value of Fl^2/EI_0, which corresponds to the crippling load.

The foregoing provides what is in practice a rapid yet effective method of estimating the crippling load for a strut of any given shape. In aeronautical applications, however, struts are invariably symmetrical about a plane perpendicular to the axis and the work consequently may be considerably simplified.

The symmetry may be introduced quite early by using as the end conditions to determine the constants A and B in the expression for M the solution of the differential equation, at

$$x=0,\ M=M_0,$$

at

$$x=\frac{l}{2},\ \frac{dM}{dx}=0.$$

If this be done the condition for crippling then takes the form

$$U(0)V'\left(\frac{l}{2}\right)-V(0)U'\left(\frac{l}{2}\right)=0,$$

i.e.

$$1-F\int_0^l\frac{x\,dx}{EI}+F^2\int_0^l\frac{dx}{EI}\int_0^x dx\int_0^x\frac{x\,dx}{EI}\ \ldots=0. \quad (36)$$

The integration now extends over half the length of the strut, and each coefficient is one integration less than in the asymmetrical case.

As before, if we throw the series into the non-dimensional form by writing

$$X=\frac{2x}{l},$$

$$I=I_0R,$$

$$\phi^2=\frac{Fl^2}{EI_0},$$

it reduces to

$$1-\frac{\phi^2}{4}\int_0^1\frac{X\,dX}{R}+\frac{\phi^4}{16}\int_0^1\frac{dX}{R}\int_0^X dX\int_0^X\frac{X\,dX}{R}$$

$$-\frac{\phi^6}{64}\int_0^1\frac{dX}{R}\int_0^X dX\int_0^X\frac{dX}{R}\int_0^X dX\int_0^X\frac{X\,dX}{R}\ldots=0. \quad (37)$$

As an illustration of the application of this method, consider the strut given in Table II., which also contains the whole of the calculations required to effect a solution.

A little explanation may be necessary for this table. The first three columns are of course derived from the dimensions of the given strut, while column IV. is obtained by the direct integration of the graph of column III. The coefficient of ϕ^2 in the series is thus $1/4\times\cdot757$. For graphical convenience column V. is introduced where the maximum ordinate in IV. is replaced by unity, all the other members being divided by ·757. This means that in the next integration the factor ·757 must be introduced.

Column VII. is likewise derived from column VI. by multiplying each term by the corresponding value of 1/R and reducing the maximum ordinate once more to unity. This again introduces another factor. The coefficients of the terms that thus enter into the series are always found at the head of the columns under the integral sign.

TABLE II

X.	1/R.	X/R.	$\int \frac{X\,dX}{R}$.	A (Previous Column reduced).	B $= \int A\,dX$.	$\frac{B}{R} = C$ (reduced).	$\int c\,dX$.	D.	$\int D\,dX$.	E.	$\int E\,dX$.
1	1·000	1	·757	1	·450	1·0	·393	1·0	·310	1·0	·300
·9	1·015	·914	·662	·875	·360	·81	·306	·778	·227	·741	·217
·8	1·062	·850	·575	·76	·280	·661	·235	·598	·160	·548	·156
·7	1·150	·805	·492	·65	·212	·542	·176	·448	·110	·408	·110
·6	1·292	·775	·414	·548	·153	·44	·128	·326	·071	·295	·075
·5	1·515	·758	·337	·445	·105	·353	·088	·224	·045	·219	·050
·4	1·878	·751	·261	·345	·066	·276	·058	·148	·026	·157	·030
·3	2·500	·750	·187	·247	·036	·200	·032	·081	·013	·105	·017
·2	3·700	·74	·111	·147	·016	·135	·015	·038	·006	·071	·008
·1	6·50	·65	·042	·056	·004	·058	·004	·010	·002	·042	·003
0	1·60	0	0	0	0	0	0	0	0	0	0
I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.

Hence, the coefficient of

$\phi^2 = \frac{1}{2} \times ·757 = ·189$

$\phi^4 = 1/16 \times ·757 \times ·45 \times ·393 = ·00837$

$\phi^6 = 1/64 \times ·757 \times ·45 \times ·393 \times ·300 = ·0001945.$

The equation to be solved is consequently

$$1 - ·189\phi^3 + ·00837\phi^4 - ·00019\phi^6.$$

Neglecting the term in ϕ^6 and solving as a quadratic this gives

$$\phi^2 = 8·6 \text{ approximately.}$$

To determine a closer approximation to the root, let

$$\phi^2 = 8·6 + \lambda.$$

Inserting this in the equation and neglecting higher powers of λ than the first, we find

$$1 - ·189(8·6 + \lambda) + ·00837(8·6^2 + 17·2\lambda) - ·00019(8·6^3 + 3 \times 8·6^2\lambda) = 0,$$

i.e. $\lambda = -1·40,$

so that $\phi^2 = 7·2$ approximately,

giving as the crippling load

$$F = 7·2\frac{EI_0}{l^2}.$$

For comparison and as a check on the result we can evaluate for the elliptical strut, which is the same as the above, given in the next section and having the value $r = \frac{1}{4}$. This gives $\phi^2 = 7·25$.

§ (15) STRUT OF MINIMUM WEIGHT.—Space does not allow us to enter into the analysis of Messrs. Barling and Webb on this subject, but for the purposes of designers the following solution is given to a class of strut one of which differs very little from the solid strut of minimum weight found by these authors. The strut is supposed homogeneous throughout, and the law of variation of moment of inertia of cross-section given by

$$\frac{I}{I_0} = \left(1 - \frac{x^2}{a^2}\right)^2,$$

where I_0 is the moment of inertia of the mid-section, I that of a section distance x from I_0, and a^2 a constant.

The crippling load is given by

$$F = \frac{4EI_0}{l^2}(1-r)\left[1 + \frac{\pi^2}{\left(\log_e \frac{1+\sqrt{1-r}}{1-\sqrt{1-r}}\right)^2}\right], \quad (38)$$

where

$$r^2 = \frac{\text{moment of inertia at end}}{\text{moment of inertia at centre}} = 1 - \frac{l^2}{4a^2},$$

l being the length of the strut.

The strut given by $r^2 = 0·05$ has, for equal thrusts, practically the minimum head resistance and minimum weight of this set, and agrees in form very nearly to that of minimum weight already mentioned.

For this value of r

$$\phi^2 = \frac{Fl^2}{EI_0} = 7\ 14.$$

§ (16) CRIPPLING OF A CONTINUOUS BEAM.—Another problem of interest is the crippling of a continuous beam under end thrust that is a strut simply supported not only at its ends but also at various intermediate points. This problem occurs in the case of the buckling of the wing spars in the plane of the wings and also the buckling of the longerons of the fuselage. Let 0, 1, 2, etc., represent the supports of a strut so loaded that the thrusts in the bays 01, 12, etc., are F_1, F_2, etc., and the lateral loads w_1, w_2, etc. Let the lengths and flexural rigidities of these bays be l_1, l_2, etc., and E_1I_1, E_2I_2, etc., and suppose the deflections of each support with respect to the line joining the neighbouring two, and the bending

moments at the supports 0, 1, etc., to be δ_1, δ_2, etc., and M_1, M_2, etc., respectively as in *Fig.* 12. Applying

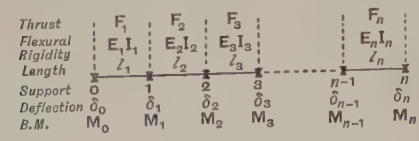


FIG. 12.

the equation of three moments to every pair of contiguous bays we obtain the following system:

Central Support of Trio.

1 $$M_0A_1+M_1(B_1+B_2)+M_2A_2 = \delta_1\left(\frac{1}{l_1}+\frac{1}{l_2}\right)-(K_1+K_2), \quad . \quad . \quad . \quad (39_1)$$

2 $$M_1A_2+M_2(B_2+B_3)+M_3A_3 = \delta_2\left(\frac{1}{l_2}+\frac{1}{l_3}\right)-(K_2+K_3), \quad . \quad . \quad . \quad (39_2)$$

. . . . . .

r $$M_{r-1}A_r+M_r(B_r+B_{r+1})+M_{r+1}A_{r+1} = \delta_r\left(\frac{1}{l_r}+\frac{1}{l_{r+1}}\right)-(K_r+K_{r+1}), \quad . \quad . \quad (39_r)$$

. . . . . .

$n-1$ $$M_{n-2}A_{n-1}+M_{n-1}(B_{n-1}+B_n)+M_nA_n = \delta_{n-1}\left(\frac{1}{l_{n-1}}+\frac{1}{l_n}\right)-(K_{n-1}+K_n), \quad (39_{n-1})$$

where A_r, B_r, and K_r have the significance already attached to them.

These constitute $n-1$ equations from which, if the bending moments at any two supports, usually 0 and n, be known, the remaining bending moments in general are uniquely determined.

These equations being linear, the solution for any one bending moment can be expressed as the ratio between two determinants. The denominator will be the same in each ratio for M_1, M_2, etc., and it is clear that if this vanishes the bending moments will become infinite. The physical meaning of this is that no matter how small the lateral load may be, the bending moments and deflections will become so large that it is illegitimate in our analysis to suppose the latter to be small, and accordingly the approximate beam theory for struts breaks down. In practice it is sufficiently accurate to regard this state as also that at which the strut will fail.

Some very elaborate experimental work has been carried through upon continuous struts of this nature to show that equation (16) does not agree with experiment. These experimenters do not realise the important fact that this equation is obtained on the assumption that the curvature of the beam may be written approximately as $EI(d^2y/dx^2)$ only when the deflections are small. Now when the thrust in a strut is small this is a good approximation, but as this thrust increases, the error increases slowly at first and then more rapidly until at the critical load the deflections and bending moments although in practice finite become infinite according to the theory. There is no necessity to carry through elaborate experimental work to prove this self-evident fact. The simple interpretation of this state of affairs is that equation (16) may always be used in practice when the thrust is reasonably below the critical. When this equation becomes seriously in error, we are so near the critical that we may regard the deflections and bending moments as being far too large for safety. This upper limit to safety is given by Euler's formula in the case of a uniform strut, and by the determinant in the case of the continuous beam now being discussed.

Writing the value of this determinant for the case of bays Nos. 1, 2, etc., as Δ_1, Δ_2, etc., we obtain:

		No. of Bays.
1	$=\Delta_1$ . .	1
$(B_1+B_2)\Delta_1$	$=\Delta_2$ . .	2
$(B_2+B_3)\Delta_2-\Delta_2{}^2\Delta_1$	$=\Delta_3$ . .	3
$(B_3+B_4)\Delta_3-A_3{}^2\Delta_2$	$=\Delta_4$ . .	4
$(B_4+B_5)\Delta_4-\Delta_4{}^2\Delta_3$	$=\Delta_5$ . .	5
. . . . .	. .	.
$(B_{n-1}+B_n)\Delta_{n-1}-A^2{}_{n-1}\Delta_{n-2}$	$=\Delta_n$ . .	n (40)

This gives a simple reduction formula enabling the determinant Δ_n for n bays to be evaluated rapidly. If the thrusts F_1, F_2, etc., be varied according to some law, suppose say that F_1, F_2, etc., are proportional to a load W, the determinant Δ_n can be evaluated for various values of W, and that load found which would make Δ_n vanish. This is the load that would give a critical for the strut and represents the uttermost limit to which W may be increased. If the lateral load on the strut causes failure at a much lower value of W than this, we may use equation (39) to evaluate the bending moments after the values of δ have been determined. If the lateral load is insignificant, W may be regarded as the breaking load of the structure.

§ (17) DEFLECTION OF STRUCTURES.—The deflected position of a structure (*e.g.* the wing structure) may easily be obtained graphically by the following method. Let ABCD, etc. (*Fig.* 13), be the original structure, in which each of the members, ties, etc., are represented in their corresponding tensions or compressions, the values of which have already been estimated approximately.

From a knowledge of the cross-sections and of the materials of each of the members, the

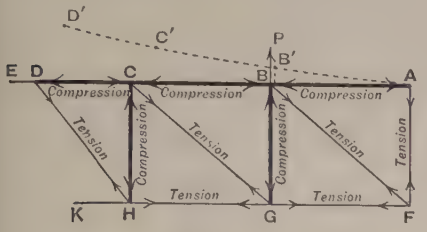


FIG. 13.

actual compressions and extensions are obtained.[1] It will be supposed that A, the central position of the upper wing, is fixed, and that F will be deflected to some point along the original line AF. Starting at *a* (*Fig.* 14), let *af* represent in magnitude and direction the deflection of F relative to A. To find the deflection of B relative to A let

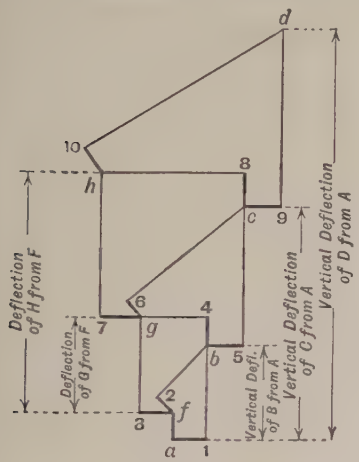


FIG. 14.

*f*2 be the deflection of B along FB and *a*1 that of B along BA. Drawing 2*b* and 1*b* perpendicularly to *f*2 and *a*1 respectively, *ab* will represent the total deflection of *b* relative to *a*. Strictly 2*b* ought to be a small arc of a circle of radius FB, but to the approximation here required this is represented as a straight line.

For the same reason 1*b* is also rigorously not a straight line. The method of compounding the component deflections can thus easily be followed through from the diagram and the vertical deflections of B, C, and D from A, and G and H from F, are obtained as indicated. It should be noted that *Fig.* 14 is not drawn to scale. B′C′D′ (*Fig.* 13) represents the deflected position of BCD, and from the values of the vertical deflections of each of these points the quantity *d* occurring in the equation of three moments is at once derived.

§ (18) ALTERNATIVE METHOD OF CALCULATING DEFLECTIONS.—The graphical method of deriving the deflections just given may be supplemented by the alternative method of calculation given below.

Suppose the structure ABC, etc. (*Fig.* 13), initially unloaded, is subjected to a force P at B. By means of the triangle of forces the tensions and compressions which this originates (viz. in ABF) are obtained. Let the force in BF be *m*P where *m* is the force when P is unity. The structure will, of course, be deflected. Let an external loading (for example, wind forces) be now applied, causing an additional deflection *d* of the structure at B. Let the corresponding extension in BF be *e*, the force in which member is now, say, R + *m*P. The work done by this extension of BF will be

$$\text{Average force in BF} \times \text{deflection in BF}$$
$$= (\tfrac{1}{2}\text{R} + m\text{P})e.$$

The total work done under the final loading will then be the sum of these for all the members

$$= \Sigma \tfrac{1}{2}\text{R}e + \Sigma m\text{P}e,$$
$$= \text{work done by wind forces for P zero} + \text{P}\Sigma me,$$
$$= \text{W} + \text{P}\Sigma me.$$

But the total work done may be regarded as composed of the work done by the extra wind loading together with the work done when B under the load P is deflected an amount *d* to its final position and this work is equal to W + P*d*. Equating these two statements and dividing by P we find

$$d = \Sigma me.$$

The deflection at B is thus obtained by multiplying the deflection in each member due to the wind forces by the force produced in that member when unit force is applied at B and taking the sum of the quantities formed. Similarly for the other joints. It may be noted in conclusion that in the calculation of the deflections of aeroplane structures sufficient accuracy may often be obtained, and the labour considerably reduced, by treating the wooden members as incompressible.

§ (19) REDUNDANCIES.[2]—In graphic statics it is usual to confine our attention to plane frames, and in such frames a member is said to be redundant when its removal does not affect the rigidity of the structure but only alters the stress distribution. The structure still

[1] Members also contract through bending, but this is neglected in the present instance. For information on this question reference should be made to R. & M. No. 792, "The Reduction of the Effective Value of Young's Modulus in Flexible Compression Members," by Dr. A. J. Sutton Pippard.

[2] See also "Strength of Structures," § (24), Vol. I.

exists as such after a redundant member has been removed, but if a member is removed which is not redundant the whole would immediately collapse. Redundant members in plane frames usually exist to add strength or rigidity to the structure.

In aeroplane structures three-dimensional frames may frequently be analysed by regarding them as being built up of a number of plane frames. Even in cases where this is not strictly true the error involved is usually very small.

Method of evaluating Forces in Redundant Members. — A redundancy depends for its operation upon the elastic properties of the material of the framework, in so far as these determine the deflections. The method that is usually adopted in treating problems of this nature is that known as the strain energy method. In this method the redundant members are first fixed upon, and supposed removed from the structure, leaving a rigid non-redundant framework ; their effect is then replaced by externally applied forces of unknown magnitude, but equivalent to those exerted by the eliminated members. The force distribution in the framework can now be obtained by direct resolution in terms of the unknown applied forces and the strain energy function built up, viz. $\phi = \Sigma \frac{1}{2} P^2 l/EA$, where P is the force in a member of which E, l, and A are the elasticity, length, and cross-sectional area respectively. In forming this expression the strain energy of the redundant members must be included. The forces in the latter are then obtained by differentiating this function with respect to each redundant force and equating the result to zero. The assumption involved in this process is that the expression ϕ giving the strain energy of the structure attains a minimum when the externally applied force replacing the effect of the redundant member becomes equal to the force in the redundant member. The establishment of the expression for strain energy, however, is an unnecessary step. The final equations can be obtained directly by a deflection theorem.

Actually, if Hooke's law applies, we proceed thus. Suppose the redundant members replaced by forces P, Q, etc., as before. Let F be the force in any remaining member, then from the geometry of the structure

$$F = aP + bQ + \ldots +, \text{etc.}, + kW_1, \ldots \quad (41)$$

where W_1, etc., are the real external loads. Since the deflections are supposed so small that the geometry is unchanged, this expression for F may be presumed unaltered after deflection. The constants a, b, etc., are obtained by force resolution or Bow's method.

Let e be the extension of the member considered; if Hooke's law holds, e will be Fl/EA, where F has the value given in (41), and l and A refer to the member. The forces P, Q, etc., may now be regarded as external forces of the nature of the force P in the previous paragraph, and, using the deflection theorem there obtained, we get

Deflection of structure under forces $P = \Sigma ae$,
" " " $Q = \Sigma be$,
etc.

The terms on the right will be linear expressions of the forces in the members, the redundant forces P, Q, etc., not appearing. Since the deflection of the structure is equal and opposite to that of the redundant member to which the force P is applied, the left-hand side will in each case be equal in magnitude, but opposite in sign, to the extension of the redundant member. We therefore obtain

$\Sigma ae = -$total deflection of the member P under its own force,

$$= -\frac{Pl}{EA} \text{ if Hooke's law holds.}$$

Similarly we obtain equations for the deflection of the other redundant members, and since there is one equation for each unknown force, the redundancies can at once be evaluated.

§(20) Stresses in the Fuselage Structure. —The discussion already given for the case of the wings applies equally well to that of the fuselage. To all practical purposes the fuselage could be regarded as composed of four plane frames connected together at the longerons. The two vertical sides of the fuselage are two such frames and the top and the bottom faces the other two. To arrive at these four frames we could suppose the cross-bracing in the bulkheads removed and each longeron and the rudder post divided into two, one part each to their respective frames. The download on the tail may in the first place be supposed divided equally between the two vertical faces, and the loads at a and a' (*Fig.* 1) due to the rudder may be supposed taken up by the bottom and top face respectively. The ends of the frames at m may be regarded as fixed. In order that the four faces when joined together should constitute a non-redundant frame, it is advisable to regard the rudder post as a bulkhead having two opposite sides very short, and to suppose the cross-bracing wires removed as in the other bulkheads. The end bay of both the upper and lower faces such as abb' undergoes corresponding modifications (*e.g.* inclusion of cross-bracing wires, etc.) which limit down to the actual case as the imaginary short members aa' and a_1a_1' become vanishingly small. The imaginary cross-bracing wires in the end bulkhead $aa'a_1a_1'$ may be regarded as

a redundancy, and together with the members aa_1, $a'a_1'$, and the short members aa', a_1a_1' forming the actual rudder post. The latter must accordingly be regarded as a redundancy which exerts a force P, say, upwards on the one vertical frame at a, and a downward force P on the other vertical face at a_1. It also acts as another redundancy equivalent to a set of forces preventing this bulkhead plane from warping. The force P as well as the redundancies in the cross-bracing of the bulkheads can be found by the method given in the previous section. It can be seen at a glance that if all the redundancies in the bulkheads are considered the work would become very laborious. For this reason, if not for any other, it becomes very necessary to supplement our theoretical investigations by elaborate experimental work upon fuselage structures under various types of loading. This remark applies with equal significance to the wing structure or any part of the aeroplane framework. W. L. C.

AEROPLANE STRUTS WITH VARIABLE RIGIDITY. See "Aeroplane Structures, Theory," § (14).

AEROPLANE WINGS, THE DOPING OF

§ (1) NECESSITY FOR DOPES.—The textile covering of the wings of the earliest gliders and aeroplanes used to be lightly rubbered before attachment in order to make them waterproof, but it was soon found that though the resistance to water was adequate the rubber quickly perished on exposure and, since the distance between the supporting ribs could not be made much less than a foot, the surface did not remain taut, even though considerable tension was applied when fixing the fabric in position: consequently the fabric bulged, especially when in flight, increasing the head resistance and deforming the profile from that designed. Similar objections applied to oil-proofed and collodion-castor-oil-proofed fabrics which were next tried. Voisin secured tautness by painting the stretched textile with starch paste, and others used glues, gums, and other sizing mixtures for the purpose; but these were in no case waterproof and became quite slack if the air was at all damp; they were also in general very liable to attack by moulds. The proofing could not be adequately protected from moisture by varnishing or covering with proofed paper.

The simultaneous requirements of tautness and waterproofness were first met in 1910, to what was then a satisfactory degree, by the Emaillite process of applying to the cloth a solution of cellulose acetate in a volatile solvent, and practically all modern "dopes" are of this nature, various additions being made to an acetate or nitrate of cellulose to secure certain properties. The nature of the ester used—nitrate or acetate, degree of esterification, and of degradation of the original cellulose, extent of "hydration," etc.—and the character and amount of the added substances which remain in the film, determine the tautness and flexibility of the doped fabric. As a rule, dopes which produce the maximum tautness give the minimum flexibility and a tendency to brittleness of the film, so that a compromise has to be made between these two desiderata.

§ (2) EFFECT OF DOPING ON STRENGTH.—All dopes which tighten fabric have a further property which is of some importance, viz. that they increase the strength of the fabric, unlike applications of rubber and other flexible proofings. Two explanations of this increase have been offered. According to the first, the penetration of the dope into the interstices between the threads produces a series of square plates which act like the web of a girder in preventing distortion of the fabric. This may be the reason of the increased rigidity of the doped fabric, but is hardly sufficient to explain the increased strength, which would apparently be due chiefly, on this view, to the interaction of warp and weft threads; the effect of transverse tension is not, however, of so high an order as is observed. A very considerable gain in strength is found, too, in cases where the dope scarcely penetrates at all. The other explanation is based on the effect of the dope on the yarn itself. It is well-known that sizing of yarns increases their strength, presumably because the size holds the individual fibres together and prevents them from the slipping which is the cause of the eventual rupture of the yarn. The action of the dope is supposed to be similar to that of size. Neither dope nor size penetrates to any large extent into the yarn, as the air imprisoned between the fibres cannot escape, so that the effect must be due to (*a*) some superficial adhesion of fibres, and to (*b*) increased friction between the internal fibres caused partly, perhaps, by a compression of the yarn by the enveloping dope film, but chiefly by the fact that the yarn is not free to untwist when tension is applied to it.

As would be expected, the gain in strength depends in some measure on the amount of dope applied. With the usual fabrics and dopes there is a relatively large increase after the application of the first coat, and succeeding coats add less and less to the strength; after some 70-80 gm. per sq. metre have been added, there is usually little or no further increase; the actual limit depends of course on the particular dope. The effect of the

dope on the tensile strength is greater, the less uniform the textile; cotton gives a smaller increase than linen, and fine linen a smaller increase than flax canvas. For the latter, Austerweil [1] found an increase in strength from 762 kg./m. to 1387 kg./m. in the warp and from 805 kg./m. to 1345 kg./m. in the weft for an increase in weight from 127 to 155 gm./m.[2] with a certain dope. The fine linen used on English machines is stronger and more irregular in the weft than in the warp; the increase in strength on doping is much greater in the weft than in the warp. The influence of uniformity of the textile on the gain in strength after doping accords well with the above suggestion as to the mode of action of the dope, since non-uniformity of strength is presumably chiefly due to variation in twist and friction of the fibres in the yarn. The films left by many dopes on fabric break down long before the test-piece breaks in a tensile test; in spite of this, such dopes cause increases in strength as great as, or greater than, those which give films which do not break before the textile.

Doping has, however, one effect on the mechanical properties of the fabric, which is obviously disadvantageous, and probably inevitable; although the tensile strength of an unwounded test-piece is higher than that of a similar piece before doping, the resistance to tearing, and especially to ripping, is decreased in every case owing to the more severe concentration of stress at the edge of the tear.

The extensibility of doped fabric is less than that of the original material, much less at the low stresses which occur in normal flight; the stress-strain curve of ordinary fabric being very convex towards the axis of strains, doped pieces give curves which are sensibly linear over an appreciable range. In the cases above mentioned, where the dope film breaks down at a load lower than the breaking load of the combination, this break-down is accompanied by an extension to an amount little less than that of the undoped fabric at the same load. The hump so formed on the curve is characteristic of most of the best tightening dopes so far produced; it is much more frequent, of course, in the more extensible direction of the fabric.

§ (3) Tautness.—Closely connected with the extensibility of the doped fabric is its tautness. Although the chief object of doping is to tighten the surface, no more scientific measure of the tautness was for many years used outside of laboratories than tapping the fabric with the knuckles to see whether a "drum note" was emitted. The fundamental frequency of the note depends not only on the tension existing in the surface, but also on the weight of the vibrating membrane; with dimensions such as occur in practice the fundamental is below or near the limit of audible frequencies, and the most prominent of the dissonant overtones which are heard depend on the position of tapping, etc. If the weight may be considered known, the frequency of the fundamental, and hence the tautness, may be evaluated by observing the resonance produced when a small motor with fly-wheel slightly out of truth is stood on the wooden framework and run at varying measurable speeds.

The practice used in several laboratories for comparison of tautness consisted in measuring the depression produced by a known small weight applied at the centre of a doped frame of given size. On this principle a portable apparatus was brought out by the General Aviation Co. in which a flat circular brass rim carried a plunger at its centre; the depth to which the plunger was depressed by a fixed spring could be read on a dial graduated in 1/1000 in. and allowed a comparison to be made between the tautnesses of two sample frames or wings. Certain objections on the score of increase in observed tension due to weight of the apparatus and the possibility of imperfect isolation of the area under test by the rim, owing to slipping, led the writer to devise a similar instrument in which these objections are to some extent obviated by the use of a fixed negative air pressure to produce the deflection to be observed; this allowed the instrument to be made much lighter, but was not quite so simple in operation. Tautness-meters of any of these types require to be calibrated; it is not sufficient to apply a certain tension by means of springs or weights in one, or even in two directions, and to read off the indication of the instrument while these tensions are continued, but the fabric stretched under the required tension must be supported on a rigid framework while the instrument is placed in position so that its weight produces the same effect on the tension as in practice. In the arrangement used by Barr and Hadfield [2] tensions could be applied in two directions at right angles and the fabric fixed in its stretched position. The variation of the tensions in each direction, produced by the application of successive coats of dopes, could be measured without allowing the dimensions to vary by an appreciable amount. This type of apparatus is the only one which allows the actual tensions produced to be measured, though its use is confined to the laboratory.

For measuring the tautness of samples fixed and doped on frames, Aston [3] recommends the use of an air-tight frame 10 in. × 10 in. internal dimensions in which the pressure is

[1] *Die angewandte Chemie in der Luftfahrt*, 1914.

[2] *A.C.A. Report T*, No. 1193.

[3] *A.C.A. Reports and Memoranda*, No. 569.

reduced to 1 inch of water below atmospheric; by means of a light spherometer the radius of curvature of the fabric is observed and the "tautness" is evaluated from the expression $T = \frac{1}{2}PR$ where T is the tautness or tension (assumed uniform) in the surface, P the difference in pressure (2490 dynes-cm.^{2}) and R the radius of curvature determined from the spherometer reading. Since it was shown in the above-mentioned paper by Barr and Hadfield that the tensions become practically identical in the two main directions after three or four coats of dope have been applied, the assumption of uniformity of tension is well enough justified for most purposes of comparison.

§ (4) WATERPROOFNESS.—If the dope has been applied carefully in a number of thin coats, the resulting film is usually found to be satisfactorily proof to the passage through it of air or of water; the films absorb also very little oil when castor or vacuum oil is placed on their surface. Appreciably large oil absorption under these circumstances can generally be traced to "pinholes" or areas which have been imperfectly doped; through these the oil passes and is readily spread by capillary action along the fabric. It is for a similar reason that some dopes appear absorbent of oil and petrol after exposure, since the surface of the film of an inferior dope becomes covered with small cracks if it is unprotected, owing to loss of residual solvent or "softener" either by evaporation or by solution in rain-water or cleansing liquids. Apart from changes of the latter nature, most dope films of modern manufacture are reasonably permanent: the deterioration of doped fabric on exposure is in nearly every case due solely to the weakening of the fabric; unless the dope contains substances which are capable of developing inorganic acidity on exposure to light, such as unstable nitrated cellulose, tetrachlorethane, etc., the tendering of the fabric is almost invariably to be ascribed to the action of light on the textile itself.[1]

§ (5) VARNISHES.—In order, originally, to obviate the cracking of the dope surface on exposure, it was found advisable to protect the dope from direct contact with the air by means of a varnish. For this purpose oil varnishes (linseed or tung) were often used, but a lighter nitro-cellulose varnish called V.114, containing some castor oil to render it flexible, was devised at the Royal Aircraft Factory and was shown to retard the development of cracks. The varnished doped fabric proved, however, to be no better than the unvarnished in respect of permanence of strength on exposure to sunlight. Ramsbottom showed that by the introduction of very finely ground opaque pigments into the varnish, the deterioration of the fabric by sunlight could be effectively avoided.[2] The pigments were at first introduced in order to render machines less visible from above, but the advantages to be obtained in this direction were found to be far exceeded by the gain in permanence: for example, a doped fabric which lost 49 per cent of its strength in 28 weeks, lost, when suitably protected, only 4 per cent over the same period. The pigment finally selected was of a dark khaki colour, made by mixing yellow ochre, Prussian blue, and carbon black: this mixture, ground in castor oil, was suspended in V.114 varnish to form what is known as P.C.10.

Efficacious as the use of P.C.10 has been proved, by numerous experimenters, to be, in protecting the fabric from the action of sunlight, there are situations in which it is not to be preferred. It was pointed out by Atkins[3] that in such bright sunshine as occurs in Egypt, the absorption of solar radiation by dark-coloured varnishes had several attendant disadvantages. Firstly, the rise in temperature of the wing above its surroundings not only tends to make the dope film brittle owing to volatilisation of the last traces of solvent, but also causes the woodwork of the planes to become warped. Secondly, the rapid cooling of the varnished surface by radiation to the sky when the sun sets or is obscured causes a large absorption of moisture by the dope and consequent slackening of the fabric. To meet these objections a reflecting surface was desirable: aluminium powder was found to be the best pigment for the purpose, since, although it is inferior to a white pigment in reducing the rise in temperature produced by insolation, it affords a much more opaque covering than does white; and opacity to actinic rays is more important than reduction of temperature. Indeed aluminium powder itself gives, in the number of coats of the varnish which are allowable, insufficient protection to the fabric and requires to be supplemented either by a subjacent coat of opaque absorbent varnish such as P.C.10 (or a redder ochre mixture P.C.12) or by a dyed dope as suggested in *A.C.A. Reports and Memoranda*, Nos. 329 and 337, respectively. Very few dyes are sufficiently stable in dope to withstand direct exposure to sunlight, though Aston has obtained satisfactory results with a few spirit soluble blacks and yellows;[4] the conditions are less severe when the dope is partially protected by the aluminium varnish.

§ (6) PIGMENTATION OF DOPES.—The increased uniformity of tautness under varying

[1] See article "Aeroplane Wings, Fabrics for."

[2] *A.C.A. Reports and Memoranda*, No. 498, 1915.

[3] Atkins and Barr, *A.C.A. Reports and Memoranda*, No. 318, 1917.

[4] *A.C.A. Reports and Memoranda*, No. 396, 1917.

atmospheric conditions, which is secured by the replacement of an absorbent by a reflecting pigment in the varnish, was noted by the writer in the Report No. 337 above mentioned. Still more satisfactory results have been described by Ramsbottom and Thomas,[1] who recommend the omission of the varnish altogether, the required opacity being secured by the introduction of pigments into the dope layer itself. Although no measurements are given in their paper of the effects of rapid variation of insolation on the tautness, they find that the pigmentation of the dope causes a very marked improvement in the direction of securing uniform tautness under varying atmospheric humidity. This improvement is most noticeable after exposure: thus, fabric doped with an unpigmented dope and examined first in an atmosphere of some 20 per cent relative humidity and then in one of 92 per cent gave, when new, degrees of slackness represented by the figures 3·2 and 6·0, and, after an exposure of 12 weeks, slacknesses of 5·1 and 9·6 in the dry and moist atmospheres respectively. Under similar conditions, except that 1½ lbs. of khaki pigment had been added per gallon of dope, the figures for the new fabric were 2·2 and 4·2, and for the exposed material 3·3 and 7·1. The figures for slackness are approximately inversely proportional to the mean tension or tautness, so that the pigmented dope not only produces greater tautness either when new or after exposure, but also causes the tautness to vary less with humidity. Earlier workers[2] who had tried the introduction of pigments into dope noticed that the film tended to be brittle and poorly adherent to the fabric; this appears to have been due either to the use of unsuitable dope or to the incorporation of too much of the pigment. If, as is the case with aluminium powder, the pigment cannot be ground to a very fine state of division, the amount of it which can safely be introduced is considerably less than the 1½ lbs. per gallon which was satisfactory for Ramsbottom and Thomas's fine khaki pigment; thus these observers confirmed the earlier statements when 1½ lbs. of aluminium powder per gallon was used, the film flaking off on bending. Very fine grinding is also essential in order that the opacity of the dope film may be sufficient, without undue increase in the number of coats to be applied. The action of pigment in regard to increasing the tautness is ascribed by these authors partly to reduction of the extensibility of the film. The obstruction offered by the particles of pigment to the diffusion of water-vapour into the film is suggested as an explanation of the superior maintenance of tautness in a moist atmosphere; but, since the differences in time required for maximum slackening were of a much smaller order than the differences in final tautness, this explanation is inadequate. Both effects may probably be due to the same cause, viz. to the surface tensions at the numerous pigment-dope surfaces which confer mechanical strength in a way similar to that occurring in piled moist sand.

§ (7) Inflammability of Doped Fabric.—In view of the serious consequences attaching to the occurrence of fire on an aeroplane, many attempts have been made to render the wings non-inflammable. It was for this reason that cellulose acetate dopes were originally preferred to those made from cellulose nitrate, since films can be made from the former which are practically non-inflammable, especially when certain softening agents, such as triphenyl phosphate, are included in the composition. Since fireproof fabrics can be produced, *e.g.* by Perkin's method of precipitating oxides of tin or tungsten on the fibres, it might reasonably have been expected that a fireproof fabric doped with non-inflammable dope would give a non-inflammable combination. Such is not the case, however.[3] Ramsbottom found that the combination burned nearly as readily as ordinary doped fabric, probably owing to the threads acting as wicks to the liquefied dope. Most of the additions which have been tried with a view to obviating this defect either weaken the dope film or are soluble in water and are lost on exposure.

In the comparison of substances which are not incapable of burning, a distinction is to be drawn between the facility with which ignition occurs and the speed of propagation of flame, properties which are not necessarily closely correlated. A careful examination of a number of dopes and varnishes was made by the writer,[4] which showed that—

(i.) Linen fabric either undoped, or doped with cellulose acetate dope, has a temperature of ignition in the neighbourhood of 380° C.; if doped with nitro-cellulose dope the ignition temperature is about 200° C. These temperatures are practically unaffected by the superposition of varnishes.

(ii.) The rate of propagation of flame in doped fabric horizontally supported is greater for nitro- than for acetyl dopes in the ratio of 2 or 3 to 1. The presence of a varnish layer makes little difference if the varnish is either P.C.10 or an ordinary oil varnish; but a pigmented oil varnish (about 1·5 oz. per sq. yard) has a blanketing effect such that it reduces the rate of burning of a nitro-doped fabric over which it is applied to about the

[1] *A.C.A. Reports and Memoranda*, No. 606.
[2] Austerweil, *Die angewandte Chemie in der Luftfahrt*, 1914; Barr, *A.C.A. Reports and Memoranda*, No. 337.
[3] *Technical Report A.C.A.*, 1913–14.
[4] *A.C.A. Reports and Memoranda*, No. 573, 1919.

same figure as that for an unvarnished acetyl-doped fabric, while over acetyl dope it makes the rate almost negligibly slow.

(iii.) Results somewhat similar to those found in (ii.) were obtained by determining the concentration of carbon tetrachloride in alcohol which was necessary in order that cylinders of plaster of Paris about 1 cm. high × 1·5 cm. diameter, soaked in the mixture, should just be incapable of igniting the fabric when stood thereon and lighted. Thus the concentrations by volume required were for acetyl dope 47 per cent, for acetyl dope + pigmented oil varnish 41 per cent, and for nitro dope 51 per cent of carbon tetrachloride.

In the same paper the interesting observation is recorded that the flame of a burning doped fabric was extinguished by a breeze of so low a velocity as 20 miles per hour, whether acetyl or nitro dope was used. Consequently the destruction of wings by fire in the air must be due to saturation of the fabric with petrol or oil. The differences between the more and the less inflammable dopes are of importance only when the machines are on the ground.

§ (8) Composition and Preparation of Dopes.—Cellulose acetate can be prepared by the action of acetic anhydride on suitable cellulose, the reaction requiring either the presence of a catalyst such as sulphuric acid, zinc chloride, etc., or a previous conversion of the cellulose to hydrocellulose. By partial hydrolysis of the resultant triacetate, or by regulation of the acetylation process, the final product may be made soluble in different solvents, ranging from chloroform to acetone and alcohol. The acetate which has hitherto proved most useful is one which is soluble in acetone. Such an acetate is also soluble in a large number of liquids and mixtures of liquids and in solutions of various solids in alcohol.[1] The main solvent which is chiefly used is acetone, and this is diluted with a mixture of methyl or ethyl alcohol with benzene, which acts as a partial solvent. Acetone was replaced to some extent by methyl ethyl ketone and by methyl acetate during the war, owing to shortage of acetone.[2] Methyl ethyl ketone is by no means so good a solvent as is acetone, but is valuable, especially in hot countries, in that it reduces the volatility of the solvent mixture. A similar reason operates, in addition to the argument of price, in the addition of alcohol-benzene mixture to acetone; if a 6–9 per cent solution of cellulose acetate in acetone is spread out into a thin film on glass or on fabric, the rapid evaporation of the acetone causes condensation of moisture from the air and precipitation of the acetate from the solution, thus spoiling the film; the presence of alcohol and benzene reduces the rate of evaporation and promotes the production of clear strong films. The concentration of the cellulose acetate which can be employed is limited in the upper direction by the excessive viscosity and difficulty of application of solutions stronger than some 9 per cent, and in the lower by the increasing cost of the solvent relative to the weight of cellulose acetate employed when the concentration is reduced below 6 per cent. The viscosity of a solution of a given strength is determined partly by the composition of the solvent mixture (alcohol, water, etc., reduce the viscosity of the acetone solution when added up to certain amounts) and partly by the nature of the acetate employed. Since, in general, acetates giving viscous solutions, which are prepared by keeping the temperature of manufacture low, yield the strongest and best films, a compromise has to be effected between the quality of the film and the permissible dilution of the solution. The grade which has been most used is one which yields a 6·6 per cent solution in acetone (6·6 gm. in 100 c.c. acetone), having a viscosity at 25° C. equal to 10–20 per cent of that of glycerol at the same temperature. The tendency at present is towards a somewhat more viscous cellulose acetate.

Solutions of cellulose acetate in acetone, or even in acetone plus benzene-alcohol, yield films on evaporation which tend to be milky and brittle unless the air is very dry or the viscosity of the solution very high. Much better films are obtained from a wide range of acetates and in humidities as high as 75 per cent, if suitable "softeners" are included in the dope. These are solid or high-boiling liquid solvents, or semi-solvents, which reduce the rate of volatilisation of the later fractions of the light solvent, and remain, more or less completely, in the dry film, preventing it from becoming brittle. The softeners which have been most used include tetrachlorethane (now out of favour owing both to its poisonous nature and to its decomposition on exposure), triacetin, benzyl alcohol, acetanilide, triphenyl phosphate, and cresylic bodies.

Nitrates of cellulose, having been commercially manufactured for a much longer time than have acetates, can be rather more readily produced of a stated viscosity and solubility and are cheaper. Many makers, especially in America, have claimed better tautness and elasticity for dopes made from nitro-cellulose, and it has even been proposed as standard practice in the U.S.A. that the first two coats of dope should be of nitrate dope to secure good tautness, and the last two of acetate to reduce the risk of fire; this is nearly the converse of standard English practice. As with cellulose acetate, so also

[1] Cf. Mardles, Moses, and Willstrop, *A.C.A. Reports and Memoranda*, No. 568, 1919.
[2] Cf. Barr and Atkins, *A.C.A. Reports and Memoranda*, No. 228, 1915-1916.

with the nitrate, various additions are made to the dope to improve the quality of the film or to reduce inflammability; for the latter purpose one proprietary dope used to contain calcium chloride, which had the advantage of reducing considerably the viscosity of the acetone solution, but had some curious effects, some only being desirable, on the behaviour on exposure.

In the preparation of dopes it is easiest, assuming the composition to be fixed, to add the non-solvents, alcohol, benzene, etc., first to the acetate (or *vice versa*), and to allow the cellulose acetate to swell thoroughly in the mixture before adding the acetone and other true solvents. If the acetone is added first, solution is slow.

Owing to the difficulty of making quantitative measurements of some of the properties of doped fabric, and especially in view of the necessity of exposure tests in the comparison of one dope with another, the British Engineering Standards Association has adopted a reference dope for such comparisons, and has specified fairly rigidly the degrees of purity and the properties of the components. The formula for this dope is as follows:

Cellulose acetate . . .	330 gm.
Triphenyl phosphate . . .	50 „
Acetone	2500 c.c.
Benzol	1200 „
Alcohol	1200 „
Benzyl alcohol	100 „

The above dope is one on which a large amount of experimental work has been done at the Royal Aircraft Establishment; the composition of the R.A.E.'s preferred dope has since been modified in order to effect certain improvements, but the proportions may be taken as being fairly representative of the best modern dopes. Five or six coats of this solution are required, when it is applied by brushing, to give a film weight of 2 oz. per sq. yard; not more than four coats are now usual for good dopes, the diminution being due either to the use of a more concentrated solution of acetate of the above viscosity, or to the substitution of a more viscous acetate in the preparation.

§ (9) Application of Dope and of Varnish.—The proportions of solvents, diluents, and softeners in dopes are selected so that they may be applied under as wide a range of atmospheric conditions as possible. Very few can be used, however, at humidities above some 70 per cent of saturation, without the occurrence of white patches in the first coat, which indicate absorption of water to the stage at which the cellulose ester begins to be precipitated. Since the white patches frequently disappear when subsequent coats are applied, especially if the air has become drier in the interval, their occurrence is often regarded as unimportant. It has been shown, however, by Atkins and Barr[1] and by Atkins and Woodcock[2] that the development of such patches is an indication of poor penetration of dope into the fabric; the adhesion between dope film and the yarn being reduced, the film is more liable to crack on exposure or with handling, though the tautness soon after the completion of doping is scarcely affected. For this reason it is recommended that the operation of doping should be carried out in a room where the humidity is as low as possible; in cool climates this may be secured by warming the doping shed, but in hot countries doping should be avoided on days when both the temperature and the humidity are high. At high air temperatures a lower relative humidity is necessary than in cool situations.

Doping is generally performed by means of a fairly large brush, the first coat being well worked into the fabric to secure good adhesion, and subsequent coats worked as little as possible so as to leave a smooth surface; the volatility of the solvents precludes the possibility of spreading the solution to anything like the same extent as is usual in oil painting. The difficulty of obtaining uniformity of covering with three or four coats has led to attempts to apply the dope by spraying; this has given good results in varnishing, *e.g.* with P.C. 10, but the composition of ordinary dopes usually requires modification, in order that they may be sprayed satisfactorily. In some works the wings to be doped are supported horizontally so that pools of dope shall not run down the surface; in others they are arranged vertically to economise floor space; there is no consensus of opinion as to which method is preferable. The organic solvents which volatilise are not only inflammable, but also have injurious effects on the operatives, if they are allowed to accumulate to any great extent; efficient ventilation is, therefore, imperative, and since the vapours are all heavier than air they are most readily removed by suction applied at the level of the floor.

§ (10) Recovery of Solvents.—Since the cost of the solvents is a large proportion of the total cost of the dope, several attempts have been made to recover them from the air of the doping shed. The problem is rendered difficult by the large size of the wings, by the fact that the solvent is a mixture usually of at least three substances, and by the low concentration of vapour in the air which is permissible in view of the necessity above mentioned of good ventilation. A measure of success has been attained by suitably enclosing

[1] *A.C.A. Reports and Memoranda*, No. 318, 1917.
[2] *Ibid.* No. 519, 1917.

a portion of the wing at a time and absorbing the vapours from the effluent air by scrubbing either with water or with cresol in limited quantity; the solution so obtained is then fractionated. The existing systems are not yet satisfactory in that they retard output to some extent and the recovery is far from complete, but they were of use during the war when shortage of solvents was acute.

§ (11) Care of Wings.—If oil, especially non-mineral oil, be splashed on doped fabric it is important that it should be removed as soon as possible, since it has been shown by Atkins and Barr [1] that oiled fabric deteriorates rapidly on exposure to sunlight. Much of the oil can be taken off by washing with soap and water, in which case no damage is done to the dope or varnish; if the oil has been allowed to soak in, the washing needs to be followed by a rubbing with benzol or carbon tetrachloride, either of which causes some damage to the varnish if this is P.C. 10, and may necessitate revarnishing. If the oily fabric has been long exposed to sunlight in the tropics it should be stripped off for fear of tendering.

G. B.

AEROPLANE WINGS, FABRICS FOR

§ (1) The Wing Structure.—The wing of an aeroplane is required to have a certain profile, fixed by aerodynamical considerations, and to be sufficiently rigid and strong both to preserve this profile under the pressures occurring in flight and to carry, not only its own weight, which may be fairly uniformly distributed, but that also of the engine, passengers, etc., which is applied over a short length at the middle of the wing. Attempts are at present being made to construct wings in which the necessary strength is obtained by using the whole aerofoil as a hollow spar, but there are considerable difficulties in the mathematical treatment of the rigidity of spars of such a shape, so that the design will probably be unsatisfactory for some time: further, the metal of which the surface is to be made must, for reasons of weight, be of such small thickness that slight corrosion might be serious, and suitably light, strong, and incorrodible alloys have probably not yet been evolved. The standard procedure at present is to use wooden or metal spars of H or similar section, with bracing wires and compression struts to contribute the required rigidity, and to cover these over with a light flexible integument, which is conformed to the desired profile by stretching it over "former ribs" spaced at frequent intervals along the spars. The covering which has been almost exclusively used hitherto consists of a light textile, which is stretched and sewn over the framework and then "doped" or coated with some solution to render it more taut and air-tight. A few machines have been exhibited in which the doped textile has been replaced either by transparent cellulose acetate sheeting or by thin aluminium or alloy foil, but neither of these alternatives has come into use: continuous materials have in general a very low tearing strength.

§ (2) The Fabric.—Of the various textile fibres available only those giving the highest strength per unit weight need be considered, namely, silk, linen, cotton, and ramie. The strength per unit weight of woven material or of sheet given by the ratio kgs. per linear metre to kgs. per square metre affords the best basis for comparison; this ratio is of the dimensions of a length, being the length of the material which would theoretically break under its own weight. The "breaking length" is preferably expressed in kilometres; for fabrics woven from the above fibres the breaking length may reach the values:

Silk	18–20 km.
Linen	16 „
Cotton	11 „

Ramie gives higher figures than cotton but is liable to rapid bacterial deterioration: several mishaps have been traced to its employment, and it has consequently gone out of use. Silk has always proved in tests made by English investigators to be inferior to linen and cotton in ability to withstand exposure to the weather, and, owing to the fineness of the yarns used in weaving it, tears more readily in spite of its high strength; recently, however, Schappe silk (*i.e.* yarn spun from silk waste) has been stated by Vignon [2] to be more permanent than linen; since the yarns used in Schappe silk are coarser, the resistance to tearing may be better also.

The figure above mentioned for the breaking length of linen refers to the weft direction of a fabric which was for a long time specified by the War Office and by the Air Department for English machines. This fabric was weaker in the warp direction, and, if the average of the strengths in both directions is used in deriving the breaking length, the value obtained is close to that for cotton. The relative merits of cotton and linen will be discussed at a later stage: in general the remarks which follow on the testing of aeroplane fabric apply to both cotton and linen.

§ (3) Weight. (i.) *Method of Testing.*—It is obviously desirable to limit the weight of the textile employed in the covering of wings to as low a figure as possible. The specification of 4 oz. per square yard as the maximum for the War Office fabric, to which reference

[1] *A.C.A. Reports and Memoranda*, No. 318, 1917.

[2] *Comptes Rendus*, 1920.

was made above, appears to have been dictated, not by any very definite estimate of the strength required, but by experience gained in the covering and doping of wings at the Royal Aircraft Factory: wings covered with linen of a certain type were found to behave satisfactorily so far as doping was concerned, and this type was then fixed. Except in cases where the weight is extremely near the limit specified, the testing of textile for weight is of the simplest character, consisting merely in accurately cutting out a certain unstretched area, preferably not less than a square metre and extending nearly the full width of the roll, and weighing this to the nearest decigram. If more precise figures are required, cognisance must be taken of the effects

(*a*) Of the relatively high extensibility of textiles at low stresses, and

(*b*) Of the variation of weight with the atmospheric humidity.

In the usual method of marking out the area to be weighed, the sample is simply smoothed out by hand on the surface of a table so as to remove obvious crinkles. This procedure is somewhat indefinite, and, if more accurately reproducible results should be required, it would be necessary to specify the application of a certain small uniform stress in both directions while the area to be tested is being marked out. Disputes attributable to this source of error do not, however, appear to have arisen, as the tolerance allowed is fairly generous, and the difference of tension applied by two observers in smoothing out the fabric is not very serious.

(ii.) *Effect of Humidity.*—The effect of the humidity of the air on the weight is more important. It has been shown by Schloesing [1] that the weight of moisture absorbed per 100 parts of the dry materials at 24° C. from air of various relative humidities is as follows, when equilibrium has been attained:

Relative Humidity per cent.	Cotton Yarn.	Boiled-off Silk.
20	3·7	4·9
40	5·4	7·2
60	7·5	9·5
80	11·0	13·6
90	14·5	17·7

For flax the figures available are 8·5 at 50 per cent, 10·6 at 70 per cent, and 14·7 at 85 per cent, for a temperature of 12° C.

The exact figures for any textile material vary slightly with temperature and with the origin and treatment of the fibre.

Instead of allowing the fabric to remain in an atmosphere of definite humidity before weighing, the procedure adopted by the textile testing houses is to find the dry weight of the material and to calculate therefrom the weight under normal atmospheric humidity by the addition of the so-called "regain," a figure which expresses the weight of water which would be absorbed by 100 parts of the dry textile after it had been exposed to air two-thirds saturated with moisture until equilibrium was established. The regain standards adopted by the Manchester Testing House and the Bradford Conditioning House, for the materials with which we are concerned, are:

Cotton	8½ per cent.
Flax	12 „
Silk	11 „

These figures refer in the first place to the raw materials: there is considerable evidence that in the manufactured state the regain is either less or is much less rapidly absorbed from the atmosphere.

The dry weight is most readily determined by weighing the sample while it is still in the drying oven. Apparatus for this purpose is sold by several firms. Experiments quoted in the *Handbook of the Manchester Chamber of Commerce Testing House*, 1913, show that a temperature of 100° C. is most convenient and will give constant weight after about forty minutes drying, under the best conditions: the temperature may, however, be raised to 110° C. without appreciable difference in the result obtained, provided the temperature distribution is uniform. The error due to weighing in the hot oven is negligible, so far as the buoyancy effect of the air is concerned, for the accuracy required in ordinary testing.

§ (4) Counts.—Strictly speaking the word "count" refers in the textile industry to the yarn employed in weaving a fabric, though it is often applied to the number of threads per unit length in either direction of the woven material. The count of yarn is in general the length per unit weight, so that the finest yarn has the highest count. The British units are the "hank" and the "pound"; for cotton, the count is the number of hanks of 840 yards to the pound, or leas (of 120 yards) per 1000 grains; for linen, it is the number of leas (of 300 yards) per pound. For spun silk, the system of numbering is as for cotton; but for thrown silk, which has the highest strength per unit weight, the number is the weight in grains of a hank of 476 metres, the coarser thread having thus the higher number. The count of the yarn used cannot be determined with any very great accuracy from tests made on the finished fabric, owing to the uncertainty involved either in stretching the unravelled yarn to remove the "crimp" imparted to it by the nature of the weaving process, or, as is often done, in stretching the fabric to the assumed loom dimensions

[1] *Société d'Encouragement pour l'Industrie Nationale*, 1893.

before marking out the length to be unravelled. The results can only be approximately correct even when the tension applied is the same as that occurring during the weaving.[1] The specification of yarn of approximately a certain count is important, however, in order to ensure a certain resistance to tearing, as will appear later.

Owing to the employment of "counting glasses" — consisting of a small lens fixed above a brass plate in which an inch or half-inch square is cut—in counting the number of threads per inch of the fabric, the word "counts" is also used in stating the closeness of weaving. In different parts of the country, and in different industries, the warp and weft threads of a fabric are styled ends, reeds, setts, etc., and picks, shots, etc., respectively. The counts of a fabric, according to the usual trade significance of the expression, do not refer to the actual number of threads per inch, which may, of course, involve fractions, but to the number of threads which can be seen in the one-inch aperture of the counting glass, which is obviously greater. For aeroplane purposes the closeness of the weave is important in view of the doping process. If the distance between threads is excessively small the dope does not penetrate between them sufficiently to ensure good adhesion of the film: if the fabric is too coarse the penetration is excessive and the solution runs through, adding useless weight to the wing and wasting the somewhat expensive dope. Relatively coarse fabrics are now calendered or "beetled" to reduce the interstices between the threads by flattening the latter to a smaller or greater extent.[2]

§ (5) Strength and Extension.—Although it is obvious that a simple tensile test on a strip of material does not represent the conditions occurring in the use of a fabric on a wing, where the stresses occur in both directions simultaneously, compound-stress tests are only made in investigatory work. For routine contractual purposes the simple test is employed, and since the object of contractual testing is merely to compare quality with that of an accepted sample and not to provide data for design, the more complicated and expensive compound-stress tests are unnecessary in this connection. The relation of simple to compound-stress tests will be discussed later.

Two types of testing machine are in use for the tensile testing of fabric specimens: (i.) with constant rate of stretching, and (ii.) with constant rate of loading.

[1] The term "regain" is sometimes applied to the extension produced by thus removing the crimp from the yarn. This use is unfortunate in view of the standard adoption of the word for the moisture absorption.

[2] See *Technical Report A.C.A.*, 1915–16.

(i.) *Constant Rate of Stretching.* — This type has found most extended use in the textile industry, owing to the relative simplicity of construction and operation and to the rapidity with which tests can be made. Actually the rate of extension is not constant, but one jaw is moved at a constant rate and the true rate of extension is conditioned to some extent by the rate of movement of the second jaw to which the stress-measuring device is attached. The latter may be a suitable spring balance, but most of the best examples are constructed with an inclination balance: the tape or chain attached to the jaw passes over and is fixed to the upper extremity of a small quadrant forming one end of a pivoted lever: the longer, initially vertical, arm of the lever carries a heavy weight at its lower end, and the height to which this weight is raised along a graduated quadrant of a circle is a measure of the stress. A suitable catch or indicator is provided to record the maximum height reached. The shape of the small upper quadrant and the nature of the contact of the chain or tape therewith are usually so designed that the graduations of the larger quadrant are uniformly spaced, but the balance should always be calibrated. Unfortunately the calibration must be performed with the balance at rest: the graduations are consequently in error, so far as the test is concerned, by an amount varying with the product of the mass and the acceleration of the moving system: these quantities will obviously vary not only with the nature and dimensions of the specimen under test and with the speed of traverse but also with the design and capacity of the machine. In specifications in which such machines are allowed, the size and make must be stated, otherwise variations in the results of tests are almost inevitable. The best-known of the machines of this type are the Schopper and the Goodbrand. *Fig.* 1 gives an illustration of the Schopper machine.

(ii.) *Constant Rate of Loading.*—The "constant rate of loading" machines are theoretically better, since the indications should not depend on the make and dimensions of the machine. The Avery machine, which is the commonest example of this type, has a horizontal beam supported on knife-edges: from one end, the shorter, is suspended the upper clamp carrying the fabric, and from the longer arm hangs a container into which small shot can be delivered at a constant rate. The second fabric clamp is fixed to a gear such that it can be lowered, by hand, at the rate necessary to keep the beam floating horizontally. When the sample breaks the supply of shot is automatically cut off and the quantity of shot delivered is weighed. The chief objection raised to this type of machine is that con-

tinuous attention is needed to keep the beam floating horizontally during the test: with constant rate of stretch machines the operator

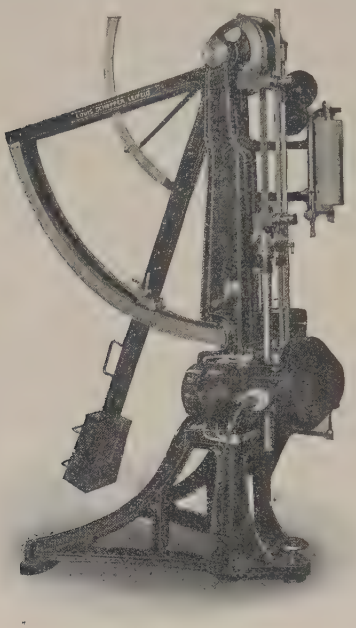


FIG. 1.

has only to start the mechanism which pulls the moving jaw. Constant rate of loading is required by all the English Government specifications for aircraft textiles. A machine by Avery used for the purpose at the National Physical Laboratory is shown in *Fig.* 2.

§ (6) CONDITIONS OF TENSILE TEST.—The factors influencing the result of a tensile test on a given fabric are:

(i.) The dimensions of the test-pieces.

(ii.) The rate of loading.

(iii.) The quantity of moisture in the specimen.

(i.) *Dimensions of the Test-piece.*—The effect of the dimensions of the test-piece was studied by Stanton and Booth [1] for a light cotton fabric, rubbered on one side, and by Barr [2] for a 4-oz. linen fabric such as is used for aeroplanes. It was found in both series of tests that for specimens above 6 in. in length, between jaws, and 2 in. in width, the breaking stress was practically independent of dimensions: when the length was less than 4 in. or the width less than 1 in. enhanced values for strength were obtained.

Since it is difficult to cut test pieces to an accurate width and at the same time to ensure having all the longitudinal threads continuous, it is usual to make the specimen initially about $\frac{1}{4}$ inch wider than is required and to fray out some threads on each side till the specified width is obtained: the projecting transverse threads are not removed.

(ii.) *Rate of Loading.*—Booth [3] found that silk fabric breaking at some 700 kgs. per metre when loaded at a rate of 250 kgs. per metre per minute showed a gradual increase in apparent strength with more rapid loading, the increase amounting to $14\frac{1}{2}$ per cent when the rate was raised to 4000 kgs. per metre per minute. Barr [4] showed that a linen fabric which broke at 1196 kgs.-metre at a rate of loading of 62 kgs.-metre-minute had an apparent strength of 1356 kgs.-metre when the rate was 4000 kgs.-metre-minute, the increase in the recorded breaking load being roughly proportional to the increase in the logarithm of the rate of loading. The experiments have recently been extended to cotton

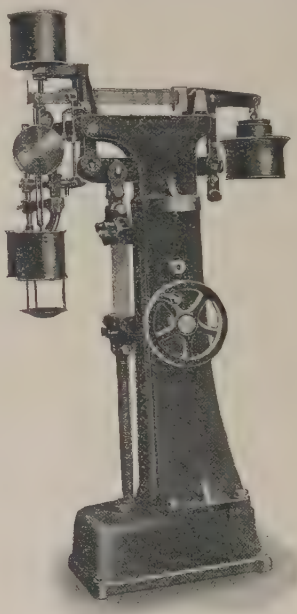


FIG. 2.

such as is used in the construction of balloon fabric, with somewhat similar results.

(iii.) *Effects of Humidity.*—The effects of atmospheric humidity have been studied by several observers. Tentative results for a cotton drill and a flax canvas were published in the *Handbook of the Manchester Chamber*

[1] *Technical Report A.C.A.*, 1909–10, p. 81.
[2] *Ibid.*, 1914–15, p. 321.
[3] *Technical Report A.C.A.*, 1910–11, p. 57.
[4] *Ibid.*, 1914–15, p. 321.

of Commerce Testing House, 1913, showing that the strength varied by ±3·5 per cent and by 4·8 per cent respectively for a variation of ±10 in the percentage relative humidity of the air of the laboratory. Barr [1] determined the variations for cotton and linen aeroplane fabric, using an enclosure around the jaws of the testing machine in which the humidity could be set at any desired figure, and found variations of 3·25 and 3·5 per cent for each 10 per cent relative humidity. As a result of these tests the suggestion was made that for contractual purposes reproducible results would most readily be obtained if all samples were soaked in water and tested wet, so that the condition of the fabric would be independent of the hygrometric state of the air: the strength of soaked samples of the above fabrics was found to be 3–4 per cent greater than that calculated for 100 per cent humidity. This suggestion was adopted, and all fabric specifications for aeroplanes during the war embodied the wet test. In the most recent specifications prepared by the British Engineering Standards Association the wet test has been dropped, and tests are required to be made under ordinary atmospheric conditions, the humidity being regulated in cases of dispute to 65–70 per cent of saturation. It is hoped that some cheap and reliable system may be evolved by which the humidity of the air may be automatically controlled, as present methods of lowering the humidity when necessary are not very satisfactory and require expensive plant.

§ (7) Methods and Results of Tests.—The American Society for Testing Materials proposed (1918) that cotton fabrics should be tested under the conditions which occur in the room, being weighed immediately before the test and again after being broken and dried to constant weight in an oven at 110° C. From the moisture content deduced from these weighings the strength is calculated to that which would have been found under standard humidity conditions. The method avoids in a satisfactory manner the necessity for regulating humidity, but entails a somewhat tedious moisture determination. The calculation is based on the assumptions (*a*) that the standard regain for manufactured cotton is 6·5 per cent of the dry weight, (*b*) that the actual regain is between 3 and 6·5 per cent, and (*c*) that 1 per cent regain between these limits causes an increase in strength of 6 per cent. The corrected strength is thus observed strength × 100 + (6 × 6·5)/100 + (6 × R), where R is the observed regain. The basis of this specification was a paper by Haven and Yeaton, published in Part I. of their *Proceedings* for that year, of which the results were briefly as follows:

(i.) *American Results.*—Cotton wing fabric—3-ply 80's yarn mercerised under tension, 70-80 threads per inch in warp and weft, weight 4 oz. per sq. yd. Full regain in standard atmosphere 8 per cent of dry weight. The tensile strength, determined on a Scott machine with rate of extension 12 in. per minute, was, from smoothed curve,

At regain per cent	2	4	6	8	10
Lbs.-inch . . .	59·3	63·9	68·1	71·7	74·0

Linen wing fabric—Courtrai flax, 94 threads per inch, 3¾ oz. per sq. yd. Normal regain found to be 9 per cent.

At regain per cent	2	4	6	8	10
Lbs.-inch . . .	58·3	68·0	76·3	82·7	87·9

Two-ply balloon fabric, diagonal doubled, total weight 11 oz. per sq. yd., 133 threads per inch warp and weft. Full regain 7½ per cent.

At regain per cent	1	3	5	7	9
Lbs.-inch	71·6	78	95	108·8	112·2

Woven tyre fabric—23 threads per inch, of No. 23 yarn plied 11 times, weight 17¼ oz. per sq. yd. Normal regain 6·5 per cent.

At regain per cent	1	3	5	7	9
Lbs.-inch . . .	192	225	248	265	274

Fabric.	Per cent Regain at 80 per cent Humidity.	Weight at 6 per cent Regain, Oz. per Sq. Yd.	Increase per cent of Bone Dry Strength for each 1 per cent Moisture Regain.
Cheese cloth	10·49	1·54	2·69
Mercerised cotton wing fabric * .	10·33	4·00	3·52
Bag sheeting	10·88	5·48	4·91
Osnaburg	10·88	8·10	5·98
	10·88	8·60	6·06
Tyre fabric *	9·00	17·3	6·67
Belt duck *	9·79	29·1	9·53
Heavy duck *	8·22	49·34	17·12

* Folded yarns.

Haven has since extended the range of fabrics tested, and in *Proc. Am. Soc. T.M.*, 1919, Part 2, gives the results shown in the above table.

[1] *Technical Report A.C.A.*, 1913–14, p. 405.

Haven deduces from these figures an average correction rate equal to 0·37 × weight in oz.-sq. yd. for the increase in strength per 1 per cent regain: actually they agree very much more closely with an average of 2·0 × (square root of weight). From the latter mean, which makes the correction proportional to the diameter of the yarn, the fabrics with folded yarns show the greatest divergences.

(ii.) *Turner's Experiments.*—Turner (unpublished communication, 1920) has tested scoured cotton fabrics weighing from 2·1 to 3·8 oz. per sq. yd. and found that these, and a grey fabric weighing 7·6 oz. per sq. yd., gave mean strengths 84, 88, 95, and 98 per cent of the wet strength when tested at relative humidities respectively 30, 50, 70, and 90 per cent of saturation: bleached fabric gave a similar gradient, but the wet strength was lower by 2 per cent than that at 90 per cent humidity. For mercerised 2/60's yarn woven into a 4·1 oz. fabric he found the fall in strength between the highest and the lowest humidity to be only equal to 6 per cent: this is in marked contrast to Haven's result. For linen fabrics weighing 3 to 4 oz. per sq. yd. the mean strengths found were 68, 72·5, 80, and 91 per cent of the wet strength when tested at relative humidities respectively 30, 50, 70, and 90 per cent. These ratios varied very considerably after weathering. Huebner has pointed out (unpublished communication) that the ratio of wet strength to "air-dry" strength of cotton varies with bleaching, with scouring, etc.

(iii.) *Humidity and Rate of Loading.*—The variation of strength with the hygrometric state of the air does not appear to be influenced by the rate of loading.[1] The large differences in "humidity coefficient" of the strength reported by different observers for fabrics of similar weight may be due in part to errors of experiment, but it is probable that most of the divergence is really due to slight differences between the materials. The increased strength produced by moisture is presumably due to increased friction between the fibres of the yarn, caused by the swelling of the fibres, rather than to an actual improvement in the strength of the fibres: this is borne out by Haven's later results, since the increase in friction would be expected to be greatest in the stoutest yarns. Consequently small changes in the surface of the fibre, due to differences in age, in bleaching, or other manufacturing operations, or in the twist of the yarn used, would be expected to affect the humidity coefficient considerably. Correction of the results of tests by the application of an average value for the coefficient will not therefore lead to such concordant figures in the comparison of the same fabric at different times or places as insistence on testing at a fixed hygrometric state, such as 66 per cent of saturation or soaked in water, though the errors should undoubtedly be less than are produced by taking no account of humidity. One other hygrometric state has been proposed, viz. testing in the "bone dry" condition: this has little to recommend it, and if tests are made by removing from an oven to the machine the moisture absorption during the transference and operation is rapid and variable.

§ (8) Compound Stress Tests.—For purposes of design it is necessary to know what relation subsists between the tensile strength and extension as found by tests on strips and the mechanical properties which pertain to the fabric under the conditions of its use on the wing where it is in a very different state. In the first place, it is always doped, and the physical properties of a doped fabric are very different from those of the original material, so different, in fact, that the characteristics of the undoped fabric are of very limited use in predicting the behaviour of the finished wing-covering.[2] In the second place, the application of a tension in one direction or of a hydrostatic pressure such as is experienced in flight results in a strain of the threads in both warp and weft directions, since the fabric is fixed to the framework at frequent intervals. This will be the most convenient place in which to treat of the stress-strain relations of a doped fabric: the problem in the case of undoped or of rubbered fabric is of little interest in connection with wing fabric, though important in airship work.

The methods of examination of fabric under compound stress which have proved most satisfactory for airship and most other fabrics, viz. the application of stresses to cross-shaped test pieces and the bursting of bags of the fabric, do not reproduce the phenomena occurring where the edges of a rectangular area are fastened, as in a wing, to a more or less rigid support. Practically the only available method is to clamp a frame on which the fabric has been stretched and doped to a chamber in which pressure can be applied. In Fage's experiments[3] air pressure was used, the chamber being connected to a large reservoir of compressed air: Turner[4] has modified the method by interposing a layer of rubber sheet below the fabric so that tests can be made on unproofed or wounded specimens without the errors attaching to pressure measurements when rapid leakage occurs. Since, as will appear in a later section, the tensile strength of fabric allows a large "factor of safety" for the stresses which are likely to arise in flight, but this factor becomes

[1] Barr, *Technical Report A.C.A.*, 1914–15, p. 321.

[2] See article on "Aeroplane Wings, The Doping of."

[3] *Technical Report A.C.A.*, 1914–15.

[4] Cf. *ibid.*, 1917–18, "On the Suitability of Cotton Fabrics."

rapidly reduced once the fabric is locally damaged, tests to destruction of unwounded fabric under compound stress are not of immediate practical application: it is in connection with testing for resistance to tearing that apparatus of this nature is most valuable. It is useful, also, however, for the determination of extensibility at low pressures, though the correlation of the results with stress-strain determinations made with simple tension machines is somewhat involved.

Apparatus for recording autographically the variation of stress with strain during the testing of strips is most readily adapted to machines of the "constant rate of extension" type, and has been much used in America for the characterisation of fabrics.[1] Such curves are chiefly useful in the comparison of doped with undoped fabric and to trace the changes occurring in doped material on exposure.[2] It is not legitimate, however, to apply the curves in all cases to the evaluation of the stresses occurring in aeroplane wings under compound strain, since the stress in the threads in one direction corresponding with a given extension is not independent of the stress existing in those at right angles to them. This is well illustrated in the case of balloon fabric by the measurements recorded by Barr,[3] and in an article by Haas translated in *Report of National Advisory Committee for Aeronautics*, Washington, 1917. A convenient method of plotting the results of stress-strain determinations made simultaneously in two directions is described by Everling.[4]

§ (9) Tearing Tests. — The effect of a wound on the strength of a fabric was examined by Booth,[5] who found that for simple tension and linear cuts there is a "danger rectangle" such that the breaking stress of a wounded specimen is independent of its area provided the dimensions of the specimen exceed those of this rectangle: *e.g.* for the cotton fabric used by him, the "danger rectangle" for a $\frac{1}{4}$-inch cut was $1\frac{1}{2}'' \times 3''$, increasing to $6'' \times 9''$ for a $\frac{3}{4}$-inch cut. In comparing two fabrics for resistance to tearing or in investigating the effect of the length of cut on the strength, it is consequently necessary that the test piece exceed this danger rectangle: for large cuts the ordinary testing machine is no longer applicable, but Fage[6] extended his measurements to cuts of $2\frac{1}{2}$ inches, using specimens up to 8 feet × 3 feet: an undoped linen fabric which had a tensile strength of 1460 kgs.-metre in the warp when unwounded had a breaking load of only 233 kgs.-metre when a cut of $2\frac{1}{2}$ inches was made in the middle of a test piece of this size. The curves connecting breaking load with length of cut for doped and undoped fabric may intersect, so that above a certain length of cut a doped fabric, initially considerably stronger than an undoped, may be the weaker.

Experiments on the resistance to tearing by the "wound" method have given results of some importance,[7] but the wound strength is not very sensitive to variations in the material. Turner has pointed out[8] that under certain circumstances, *e.g.* near points of attachment of rigging, tearing of an aeroplane fabric may occur by a method more closely resembling the ripping of fabrics by hand, and that the resistance to ripping is much more sensitive to changes in structure or condition of the fabric than is the wound-strength. He describes two procedures for estimating the "rip-strength." In the first a specimen $2'' \times 6''$ is cut lengthwise down the middle for 4 inches, and the tear continued by placing the two limbs in the jaws of the machine so that the line of cut follows the line joining the centres of the jaws. In the second, a tongue $2'' \times 4''$ is cut from the middle of a $6'' \times 8''$ test piece, and the tongue gripped in one jaw while the whole width is gripped in the other. The second method appears to be preferable, as giving a more symmetrical arrangement. The rip strength is found to be greater, the greater the freedom of the yarns to slide, and the coarser and less extensible the yarn: continuous materials such as sheet metal tear by ripping much more readily for a given tensile strength of unwounded substance than do fabrics.

Only a few tearing tests have been made under compound strain, and these mostly by the "wound strength" method, though Walen has recently[9] given the results of some tongue tests on fixed fabrics. Fage[10] gives a comparison between the results of tensile-tearing and pressure-tearing experiments. For the former a sheet of fabric $6'' \times 3''$ to $6'' \times 6''$ was subjected to a constant stress in the warp by means of the Avery machine, and a transverse central wound made by a tapering blunt knife which enlarged the cut until the applied stress became the tearing stress for the specimen: the length of the cut for which this occurred was obtained from the depth of penetration of the knife. The bursting tests were made by applying a constant air pressure to a sheet of doped fabric stretched over a frame $24'' \times 6''$: a

[1] See *Report of National Advisory Committee for Aeronautics*, Washington, 1917.
[2] See Barr, *Technical Report A.C.A.*, 1912–13, 1913–14, and 1914–15, and Austerweil, *Die angewandte Chemie in der Luftfahrt*, 1914.
[3] *A.C.A. Reports and Memoranda*, No. 231, 1915.
[4] *Zs. für Flugtechnik und Motor-Luftschiff-Fahrt*, Jan. 31, 1920.
[5] *Technical Report A.C.A.*, 1910–11.
[6] *Ibid.*, 1914–15.
[7] See *A.C.A. Reports*, 1913–15.
[8] *Ibid.*, 1918–19.
[9] *Report of National Advisory Committee for Aeronautics*, Washington, 1920.
[10] *Technical Report A.C.A.*, 1914–15.

wound was then made in the fabric by means of the same knife, the shape of which was such that it blocked up the hole so as to prevent rapid leakage of air. From the tensile tearing strength for a certain length of cut, and the extension at rupture, the bursting pressure for a specimen of the dimensions of the samples used for the bursting tests was calculated from the relation pressure = tensile strength ÷ radius of curvature: the bursting pressures so deduced were plotted against length of cut on the same diagram as the results of the bursting tests, and the two series gave good agreement. In these tests the warp threads were severed, the warp in the bursting experiments being in the shorter direction of the frame: since the linen fabric used was more extensible in the warp than in the weft, the stresses on the weft at rupture must have been considerable. In the usual method of applying this fabric to the wings, the weft is the direction which is fixed at the more frequent intervals, *i.e.* to the ribs; the stresses in the direction at right angles to the shorter length would be smaller for a given extension in the weft on this arrangement than for the same extension in the warp in Fage's experiments. It may hence be concluded that, for wounds in doped linen of the nature considered, stresses in the direction of the length of the cut are without influence on the tearing strength.

§ (10) Stresses in the Fabric of a Wing.—Since the distance between the ribs is small compared with the chord of the wing, most of the pressure occurring during flight will be carried by the yarns at right angles to the ribs, especially if, as is usual, the extensibility is the smaller in this direction. Under the uniform air pressure, the fabric will bulge so that the section perpendicular to the ribs is an arc of a circle: for the small extensions occurring it has been shown [1] by Jones that the resulting tension is given by

$$t = pd\sqrt{\frac{1}{24e}},$$

where t is stress per unit length of the fabric,
p, pressure per unit area,
d, distance between the ribs,
e, extension of fabric per unit length.

The distribution of pressure over the surface of some typical wings has been determined by wind-channel experiments; for a certain aerofoil it was found that the maximum suction which can occur on the upper surface is $-1{\cdot}5\rho v^2$, and the maximum pressure on the lower surface is $+{\cdot}5\rho v^2$, where ρ is the density of the air and v the air speed: the greatest possible pressure will thus occur if there is a leak in the wing on the lower surface at the point of maximum pressure, the rest of the wing being air-tight, and will amount to $2{\cdot}0\ \rho v^2$, tending to suck the fabric off the upper surface. These conditions could only be realised when the machine flattens out very suddenly after a steep dive. For the case considered by Jones, ribs 0·92 foot apart, air speed 100 m.p.h., the lift on the wings being more than six times the weight of the machine, the maximum tension in the weft of the fabric is calculated to be about 14 lbs. per inch, that on the warp being assumed zero, and the maximum force tending to tear the fabric away from the rib is about 8 lbs. per inch run.

Fage has pointed out [2] that in the neighbourhood of the leading and trailing edges the assumption that all the load is taken by the weft or transverse threads is not justified, and has calculated by a somewhat laborious method of approximation the stresses in warp and weft at different distances from these edges. For a slightly different wing, in which the rib spacing measured 14 inches, with similar abnormal conditions of loading, speed 100 m.p.h., and lift four times the weight of the machine, he calculates, allowing a factor of safety of 2 on the maximum air pressures deduced from the wind-channel experiments:

Upper surface of wing, maximum longitudinal (warp) stress, 20·5 lbs./in. at the nose end; maximum transverse (weft) stress, 23·1 lbs./in. at a distance of $\frac{1}{8}$ of the chord from the leading edge.

Lower surface of wing, maximum longitudinal stress, 23·6 lbs./in. at the nose end; maximum transverse stress, 23·6 lbs./in. at a distance of $\frac{1}{7}$ of chord from leading edge.

From his curves [3] connecting tearing stress with length of cut for the fabric considered (4-oz. linen fabric, about 90 threads per inch) he estimates that a tear of about 2 inches would be necessary before the fabric could fail under the most severe conditions of loading occurring in flight.

The high figure suggested by Jones [4] for the force tending to pull the fabric off the rib led to experiments at the Royal Aircraft Factory on the best method of fixing the fabric to the framework. Instead of the older method of tacking the fabric either direct or *via* an external lath to the surface of the rib, the expedient was tried of sewing the top and bottom sides of the fabric to the rib by strong waxed cord passing through the fabrics and round the rib, the cord being knotted after each stitch: this was found to

[1] Cf. Jones, *Technical Report A.C.A.*, 1912–13.

[2] *Technical Report A.C.A.*, 1914–15.
[3] Fage, *Technical Report A.C.A.*, 1914–15.
[4] Jones, *Technical Report A.C.A.*, 1912–13.

give greatly increased strength, and is now adopted on all English machines. The stitches are made every three inches along each rib, and the cord is subsequently covered with frayed tape solutioned to the fabric so as to present a smoother surface.

§ (11) Effect of Exposure on the Textile. (i.) *Effect of Sunlight.*—It was recognised very soon after the development of the aeroplane had begun that a comparatively short exposure of light cotton, linen, or silk fabrics to the weather was sufficient to produce serious loss in strength, especially in the summer, when a month's weathering caused a reduction of 40 per cent in the strength of an undoped linen and of nearly as much for a doped linen.[1] That most of this deterioration is due to the action of the actinic rays of sunlight was shown by comparative experiments under ruby glass and colourless glass.[2] This view was confirmed and amplified in a series of reports to the Advisory Committee for Aeronautics from 1915 to 1919, both from the National Physical Laboratory and, especially, from the Royal Aircraft Establishment. It was found that when light was excluded by means of the dark khaki-coloured protective varnish, P.C. 10, devised by Ramsbottom for application over the doped linen, the rate of loss in strength was reduced to a very small figure, *e.g.* 20 per cent for one year's exposure at Farnborough. The deterioration was more rapid and the effect of an opaque covering more pronounced in tropical or sub-tropical exposures.[3] The writer made prints on bromide paper through specimens of doped fabric weathered in Egypt which had received coats of P.C. 10, red, white, and blue enamels, black paint and dope only, and found that the order of merit in respect of opacity to such rays as act on silver bromide was the same as the order in respect of strength retained. Aston[4] attempted to locate more definitely the position in the spectrum of the destructive rays, and showed that in exposure to the mercury arc lamp the strong radiations at 3660 A.U. and 3130 A.U. were effective in weakening linen threads, while the visible rays were not. He was not able to obtain corroboration of these results in English sunlight, however, owing to the small intensity of the light dispersed in his spectrograph: the probability of divergence between the effects of exposure to the mercury arc lamp and to sunlight had already been noted by Barr[5] in connection with balloon fabrics, tropical exposure of which deteriorated the rubber faster than the textile, while the reverse was the case in exposure to the mercury lamp. Certain spirit-soluble black and yellow dyes introduced into the dope were found by Aston to have a protective effect, in exposures of doped fabric to the weather, equal to that afforded by the usual pigmented varnish. The same degree of protection was also obtained by Ramsbottom and Thomas by the introduction of opaque pigments into the dope.[6]

(ii.) *Other Destructive Agents.*—Though sunlight is normally the chief agent in causing deterioration of fabric on exposure, other causes may also operate in certain circumstances. In the neighbourhood of manufacturing centres the acidity present in the air has been shown by Lang[7] to be a source of danger: mineral acid left in the fabrics in some stages of its treatment before doping, or generated in an unstable dope during exposure, is very potent in producing "tendering." Some idea of the quantity of acid necessary to cause appreciable weakening may be obtained from a paper by Barr and Hadfield.[8] Under improper conditions of storage, or on exposure in humid climates, much of the deterioration is due to moulds or bacteria.[9] Atkins found also that the impregnation of the doped fabric with castor oil, which may occur locally in certain classes of aeroplane, causes an increase in the rate of deterioration on exposure to sunlight.

§ (12) Relative Merits of Different Textiles. (i.) *Linen.*—For many years the fabric preferred by the aeronautical authorities in England for covering the wings of aeroplanes has been a plain unbleached linen (specification 17 of Royal Aircraft Factory), which was required to have:

> Weight not more than 4 oz. per sq. yd.
> Ends not less than 80, picks 90 per inch.
> Tensile strength, warp 90 lbs. per inch, weft 90 lbs. per inch when tested on strips $7'' \times 2''$ at 150 lbs. per inch per minute.

Though the details have varied a little, a fabric of this type, in which the weft has usually been considerably above the minimum specified, has been the standard with which most others have been compared. This fabric, if size is excluded as required by the specification, is readily doped to give a smooth, taut surface, and the dope causes an increase in tensile strength of the order of 8 per cent in the warp and 25 per cent in the weft.

[1] Barr and Thomas, *Technical Report A.C.A.*, 1912–13.
[2] Barr, *Technical Report A.C.A.*, 1914–15.
[3] Atkins and Barr, *A.C.A. Reports and Memoranda*, No. 318, 1917; Turner, 1919.
[4] *A.C.A. Reports and Memoranda*, Nos. 396, 1917, and 585, 1919.
[5] *Technical Report A.C.A.*, 1916–17.
[6] *A.C.A. Reports and Memoranda*, No. 606, 1918.
[7] *Ibid.*, No. 288.
[8] *Ibid.*, No. 635, 1918.
[9] Atkins and Barr, *loc. cit.*, for Egyptian, and Turner, *Reports and Memoranda*, No. 582, 1919, for Malay exposure.

(ii.) *Cotton.*—On Farman machines cotton was regularly used: the fine material was normally more uniform in strength of warp and weft than the linen, and the increase in strength on doping was considerably less. The weft strength of the doped fabric was consequently much lower than that of linen for the same weight. Probably owing to the very much greater extensibility of the weft in these plain weave cottons than in linen, it was usually found that the tautness after weathering was inferior to that occurring with the standard fabric. The difference in tensile strength was accentuated in the tearing strength for small wounds, though in bursting experiments the greater extensibility of the cotton made the difference in factor of safety less marked.[1] The resistance to ripping of these fabrics was not more than one-third of that of linen of the same weight. Attempts were made to overcome the above defects by using stout reinforcing threads to localise any damage, but all such reinforced fabrics have been found to have a rather high consumption of dope.

Very much better results were obtained in the U.S.A. by the use of a mercerised cotton yarn, either two- or three-ply. The development of this material is described by Walen,[2] the stages in improvement being correlated with the shape of the stress-strain diagram autographically recorded by the testing machine used. With the fabric finally evolved, the strength and the preservation of tautness were scarcely inferior to linen.

Chiefly, it would seem, owing to scarcity of fine linen, German and French machines during the war were largely covered with a much coarser fabric than the above linen. It appears probable, however, that the use of coarser linen is actually advantageous, as has been suggested by Barr and by Turner,[3] especially if the fabric is calendered to reduce the penetration of dope by diminishing the interstices between the threads. Turner prefers, for example, a 4-oz. fabric, with 50 ends and 50 picks per inch, heavily beetled. Fabric woven of stouter thread has normally rather lower tensile strength for a given weight, but higher resistance to tearing and apparently also to weathering.

Between the standard linen fabric and one made from two-ply mercerised cotton yarn there is little to choose: the linen is, however, rather stronger, especially in resistance to tearing, than the best cotton fabric so far constructed. With a coarser linen, such as that indicated by Turner, the advantage over cotton would be still greater. As regards weathering, no figures are available for mercerised cotton, but, from a series of exposures at Berbera and Malacca, Turner[4] concludes that ordinary cotton resists the action of light better than does linen, but is rather more susceptible to damage by moulds in a hot and humid climate. On exposure to light at Berbera silk loses strength very rapidly indeed: the protection afforded by an opaque covering is adequate in a dry locality, but at Malacca deterioration of silk is more rapid than that of linen when both are similarly protected. These conclusions as to the relative sensitivity of linen, cotton, and silk to light are in agreement with the results of Aston's experiments,[5] using the mercury arc as source of light, except that Aston found linen rather less sensitive than cotton. Both observers note that thick threads suffer a smaller percentage loss in strength than thin yarn of the same kind of fibre: this may perhaps explain why Vignon (see § (2)) found a Schappe silk fabric to withstand exposure to a mercury arc better than the linen with which he compared it, but this fabric is to be further examined.

G. B.

[1] See Turner, *Technical Report A.C.A.*, 1917–18.
[2] *Report of National Advisory Committee for Aeronautics*, Washington, 1917.
[3] *Technical Report A.C.A.*, 1914–15 and 1918–19.
[4] *Technical Report A.C.A.*, 1919–20.
[5] Turner, *Technical Report A.C.A.*, 1917–18.

AILERONS: movable portions of aeroplane wings which can be actuated by the pilot through control wires and thus serve to maintain the aeroplane in any desired path. See "Aeroplane Structures, Theory of," § (3). See also "Aeroplane, Component Parts of."

Strength tests on. See "Aeroplane Structures, Experiments," § (18).

AIR FLOW AROUND AN AIRSCREW, NATURE OF THE. See "Airscrew, The," § (3).

AIR-HYDROGEN MIXTURE ANALYSIS. See "Diffusion through Membranes," § (7).

AIR LOG: an instrument used on aircraft for recording the distance flown through the air. See "Aircraft, Instruments used in," § (5).

AIR SPEED INDICATOR: instrument used on aircraft for measuring speed through the air. See "Aerodynamic Research, Full Scale," § (3), and "Aircraft, Instruments used in," § (6).

AIR TEMPERATURE, decrease with height. The temperature of the air decreases on the average about 6·5° C. per kilometre. See "Aircraft, Instruments used in," § (2); also "Aircraft Performance," § (2). See also "Barometers and Manometers," § (16), Vol. III.

AIRCRAFT: EXPLANATION OF TERMS IN COMMON USE

The motion of any aircraft, whether lighter or heavier than air, is most readily described with reference to three lines or axes fixed in the body and drawn through G, its centre of gravity. Of these the first—the axis of X—points in the forward direction and coincides approximately with the axis of the airscrew—the longitudinal axis of the craft. The axis of Z, the normal axis, lies in the plane of symmetry and is perpendicular to the X axis; the third, the axis of Y, the lateral axis, is at right angles to the other two and is directed towards the right. These directions are illustrated in *Fig.* 1.

The motion with which we are concerned is that relative to the air in the neighbourhood of the machine. It depends on the motion of the air—the wind—and on that of the

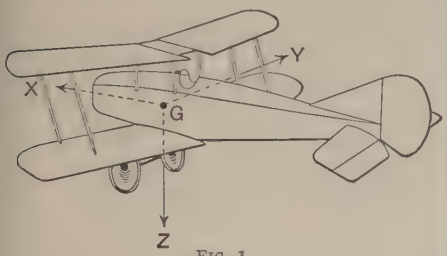


Fig. 1.

machine, both relative to the ground. If we imagine a velocity equal and opposite to that of the machine conferred on both the machine and the air, the relative motion of the two is unaltered, but the machine is reduced to rest. The resultant motion of the air, obtained by combining the velocity of the wind with a velocity equal and opposite to that of the machine, thus gives the relative motion required. In this way we obtain both the amount and direction of the *Relative Wind.*

Angular motion about the X axis is described as *Rolling*, about the Y axis it is *Pitching*, and about the Z axis *Yawing*. In uniform horizontal motion the Y axis is horizontal and at right angles to the direction of motion which lies in the vertical plane of symmetry, inclined at no very large angle to the X axis.

The angle between the direction of motion and the chord of the wing is called the *Angle of Attack* or *Angle of Incidence.*

In turning to the right the control column is moved to the right, the right wing of the machine is depressed, the left wing is raised; the machine rolls about the X axis; it is said to be *Banked*, and the angle which the Y axis —the line joining the wing tips—makes with a horizontal plane measures the *Banking Angle*; if the turn is to the left the banking takes place in the opposite direction.

To define the angles of yaw and pitch imagine the aeroplane placed with the X axis along and opposite to the direction of the relative wind. Rotate it about the Z axis through an angle β, this gives the angle of yaw; then rotate it about the Y axis in its new position about an angle α, this gives the angle of pitch.

Or again, reversing the operations and starting with the machine in any position relative to the wind, consider a plane passing through the Y axis and the direction of the relative wind; the angle which the X axis makes with this plane is α, the angle of pitch. Then imagine the machine to be rotated about the Y axis until the X axis is brought into the plane in question; the angle between the new position of the X axis and the direction of the relative wind is β, the angle of yaw. Finally, turn the machine until the X axis lies along the relative wind and let it be rotated about this axis in its new position until the Y axis is horizontal and the plane of symmetry therefore vertical; the angle turned through measures the angle of roll or bank. The angles are to be considered positive when the directions of rotation are from GY to GZ, GZ to GX, and GX to GY respectively.

In normal flight an aeroplane moves so that the direction of motion of the wings relative to the air is at right angles to their span; if the motion has a component in the direction of the span, *i.e.* along the axis of Y, the machine is said to *Side Slip.*

If the angle of incidence is increased beyond a certain critical value dependent on the form of the wings the lift suddenly drops in value and the machine ceases to be under control. It is then said to be *Stalled.*

AIRCRAFT, INSTRUMENTS USED IN

§ (1) Climbmeters.—When testing aeroplanes to measure their maximum rate of climb at any height it is convenient to have an instrument to show the approximate rate of climb at the moment, so that the pilot may get the best possible performance out of the machine. Such an instrument is also useful for balloonists. The general principle on which these instruments are constructed is as follows.

A vessel very highly thermally insulated (in practice, usually of the "Vacuum" type) communicates with the outer air by a very small leak. Hence, if the instrument is being carried upwards so that the pressure outside is falling uniformly, the pressure inside will be higher than the pressure outside, and finally an equilibrium condition will be attained. The excess of pressure within is then just sufficient to cause air to flow through the leak at a rate which will allow the inner pressure to fall at the same rate as the outer.

The excess of pressure inside the vessel is used as a measure of the rate of climb, and is usually shown on a simple liquid gauge.

The leak from the insulated vessel to the outer air may be of two types: (1) by a long capillary tube, or (2) a very small hole in a thin metal diaphragm. The action of the instrument is somewhat different in the two cases. In the former the rate of climb is equal to

$$C\frac{p}{\rho}dp$$

and in the latter to

$$K\frac{p}{\rho^{\frac{3}{2}}}dp^{\frac{1}{2}}$$

where C and K are constants,
p and ρ = the pressure and density of the air at the height concerned,
dp = the difference of pressure between the inside and outside of the vessel.

It will be seen that in the first case the scale with a U tube liquid gauge will be uniform, while in the second it will be contracted for low readings and expanded for high readings, which is a disadvantage.

The first or second type of instrument could be made to read correctly at all heights if the temperature distribution in the atmosphere were such that p/ρ or $p/\rho^{\frac{3}{2}}$ respectively remained constant at all heights. Actually, the existing distribution is such that they both have about equal height corrections.

The constant of the instrument can be best found by blowing air into the vessel and noting the time required for the pressure to fall to, say, half its initial value. Liquid gauges are the most convenient, since it is necessary that the change of volume due to the movement of the gauge should be very small compared with the volume contained in the vessel, otherwise the expressions given above are not true, and the sensitiveness of the instrument is decreased.[1] The sensitiveness of the instrument is governed by the size of the leak, but it cannot be increased too much, otherwise the very small leak required causes the instrument to have a serious lag. The liquid gauge has a disadvantage that it is affected by accelerations of the aircraft, and on suddenly increasing the rate of climb the instrument may first indicate a decreased rate of climb owing to the effect of the vertical acceleration.

A modification of the climbmeter is the "Statoscope," an instrument for showing whether the aircraft is flying at a constant height (strictly constant pressure). In this instrument the leak is entirely closed up, and the liquid pressure gauge is replaced by a drop of liquid in a V-shaped glass tube fixed with the point of the V downwards. Each end of the V has bulbs, so that if the drop of liquid is forced to one end it breaks and runs down to the bottom of the V, where it collects again. Statoscopes are also made using pressure gauges of the diaphragm type.

§ (2) Altimeters.[2]—On all aircraft it is naturally desirable to have means of knowing at any moment the height above the ground. For this purpose there is only one convenient method for general use, viz. by the measurement of the atmospheric pressure. For this purpose an aneroid is carried whose mechanism is similar to that of the ordinary aneroid barometer. The dial, however, is graduated in heights and is adjustable so that it can be set to read zero on the ground before starting each flight. The instrument is also adjusted so that the scale of heights is uniform, and not as in the ordinary aneroid, where the pressure scale is uniform. This avoids a small error when the scale is set to read zero at a pressure above or below the normal pressure.

In order to determine the difference of height between two points at which the atmospheric pressures have been found it is necessary to know the temperature of the air between these two levels. But as an altimeter, to be a serviceable instrument, must show at least approximate heights directly, an assumed temperature of the air is used when graduating the instrument.

When altimeters were first made for use of mountaineers, etc., little was known about the distribution of air temperature with height, and it has been the custom in the past to assume a uniform air temperature of 10° C. (50° F.) for all heights. Observations by "*ballons-sonde*" have shown that the air temperature decreases on the average about 6·5° C. per kilometre (approx. 3·5° F. per 1000 ft.) up to the height of the bottom of the stratosphere. This height is on the average about 11 km. in the temperate regions, but is lower nearer the poles and higher nearer the equator; the actual height of the stratosphere also varies irregularly from day to day, being in general high when the atmospheric pressure is high and *vice versa*. In future a temperature given by a formula such as

$$\theta = 15 - 0{\cdot}0065h$$

where θ is temperature in ° C.,
h = height above sea-level in metres,

will probably be taken as the standard for calibration of aneroids up to a height of 11 km. Table I. shows the pressure, temperature, and density of the air given by this assumption.

[1] See Advisory Committee for Aeronautics. T 910.

[2] See also "Barometers and Manometers," §§ (16), (17), Vol. III.

TABLE I

Height in Kilometres.	Pressure in Millimetres Hg.	Temperature ° C.	Density Kgms./Metre³.
0	760	15	1·225
1	674·1	8·5	1·111
2	596·1	2	1·006
3	525·7	− 4·25	0·9089
4	462·2	−11	0·8189
5	405	−17·5	0·7359
6	353·7	−24	0·6595
7	307·8	−30·5	0·5889
8	266·8	−37	0·5249
9	230·4	−43·5	0·466
10	198·1	−50	0·4124
11	169·6	−56·5	0·3636
12	144·8	−56·5	0·3106
13	123·7	−56·5	0·2652
14	105·6	−56·5	0·2265
15	90·25	−56·5	0·1935

§(3) ERRORS OF ALTIMETERS IN AEROPLANES.

(i.) *Instrumental Temperature Errors.*—These errors due chiefly to change of elasticity of the spring and diaphragm with varying temperature are usually fairly well eliminated in good instruments by the use of bimetallic levers, or by leaving a definite amount of air in the diaphragms. It may be noticed, however, that compensation by these methods can only be perfect at one pressure.

(ii.) *Lag or Creep Error.*—This is always present in all aneroids and is due to the fact that quite apart from frictional effects the diaphragm does not take up its final position for a long time after a change of pressure. The error naturally depends on the immediate past history of the instrument and may amount to several hundred feet in a bad instrument. By careful design or choice of suitable materials the error can now be reduced to from 10 to 20 ft. after the instrument has been taken to 25,000 ft. at a rate of 1000 ft. per minute.

(iii.) *Calibration Errors.*—The dials of aneroids are first engraved with uniform height intervals, and the aneroid mechanism is adjusted to make the instrument fit the dial by the process known as "ranging." It follows that the calibration can never be perfect at all heights, and for accurate work a correction should be applied by testing each instrument.

(iv.) *Errors due to Variation of Atmospheric Temperature and Pressure.*—Since the altimeter must be calibrated on some definite assumption regarding the variation of pressure with height, it follows that there must be an error when the assumed conditions do not occur. The basic relation between pressure and height is given by

$$h = -\frac{1}{g}\int\frac{1}{\rho}\,dp,$$ where $\begin{cases} h = \text{height}, \\ \rho = \text{density of the air}, \\ g = \text{acceleration due to gravity}, \\ p = \text{pressure}. \end{cases}$

From this it is seen that the density of the air between the two levels is the important quantity. It is fortunate for this purpose that though the temperature and pressure of the air at any height vary from day to day, yet they tend to change together (below the height of about 9 km.), so that the standard deviation of the density at any height is not excessive.[1] Provided a relation of pressure to height is used which agrees with the actual average values, the probable error of the altimeter reading in Europe is not very great. On the old assumption that the temperature of the air was constant at 10° C. at all heights, the errors—especially at great heights—might be much greater. Table II. shows the limits within which the errors will lie on (*a*) one out of two occasions, and (*b*) 99 out of 100 occasions, according to the method of calibration used.

TABLE II

Height in Kilometres.	Error in Metres is within the following Limits on					
	1 out of 2 occasions.		99 out of 100 occasions.		1 out of 2 occasions.	99 out of 100 occasions.
	Air Temperature 10° C.				Average Actual Temperature.	
0	..	..	..	..	..	..
1	+ 13	− 13	+ 52	− 52	± 15	± 50
2	+ 58	+ 2	+ 138	− 78	± 30	± 110
3	+ 135	+ 49	+ 257	− 73	± 45	± 165
4	+ 209	+ 91	+ 377	− 77	± 60	± 225
5	+ 337	+ 183	+ 557	− 37	± 75	± 295
6	+ 491	+ 299	+ 767	+ 23	± 95	± 370
7	+ 683	+ 457	+ 1010	+ 130	± 115	± 440
8	+ 903	+ 637	+ 1286	+ 254	± 135	± 515
9	+ 1070	+ 770	+ 1498	+ 342	± 150	± 580

[1] See W. H. Dines, *Geophysical Memoirs*, No. 13, Meteorological Office, London; also *Advisory Committee for Aeronautics Report*, Met. 46.

(v.) *Variation of Pressure due to Speed of the Aircraft.*—If an altimeter be enclosed in a case with, say, one opening, which is exposed to the relative wind, the pressure in this case will vary from the true static pressure at its height by an amount not exceeding $\pm\frac{1}{2}\rho v^2$ according to the relation of the opening to the relative wind (where ρ is the density of the air and v the velocity of the relative wind). Thus the aneroid would show different heights according to the position of the opening. At the high speeds attainable with aircraft it is possible that this error may amount to 200 metres, or more. The same effect will occur in the space in which the aneroid is contained in the aircraft, the magnitude of the effect depending on the positions of the openings from this space to the relative wind. Fortunately, in nearly all aeroplanes the pressure at the instrument board is very nearly equal to the true static pressure of the surrounding air at that height, thus the error is negligible. A larger effect may, however, occur in machines of special shape, and should not be neglected without investigation if great accuracy is required. Should the effect reach appreciable magnitude it can always be overcome by placing the altimeter in an air-tight vessel which is connected to the static side of the air-speed indicator.

§ (4) Turn Indicators.—The navigator of a ship at sea can steer a straight course even though the ship may be enveloped in a dense fog, by reference to his magnetic compass, which is so satisfactory that no other instrument is carried. On aeroplanes, however, the case is very different. In the article on Compasses (which see) it is pointed out that the magnetic meridian is necessarily defined by the directions of total magnetic force *and of gravity.* Also, that since on aircraft during a turn the "apparent" direction of gravity may be very different from the true vertical, the indications of the compass may be very misleading. So much is this the case that a turn to east or west, from an originally northerly course, may actually be shown in the wrong direction. Again, during a "spiral," or "spin," the compass slowly oscillates backwards and forwards, indicating that the machine is following a sinuous course. If the aeroplane be in cloud, the pilot may have no idea whatever which way he is turning or spinning, and is therefore quite unable to stop turning and bring his machine into a straight course again.

From this it will be seen that the need of some form of instrument to indicate the direction of a turn, and roughly the rate of turn, is very great. It is not required that the rate of turn should be exactly indicated, since the instrument is primarily used to enable the aeroplane to be flown straight when the pilot wishes it. So far, only two types of turn indicator have been used—the "Static Tube" type and the gyroscopic type.

(i.) *Static Tube Method.*—Two "static tubes," similar to those used as part of the "heads" of air-speed indicators, are mounted near each wing tip, and pipes are led from these to a sensitive differential pressure gauge on the instrument board. Since the pressure in the "static" tubes is independent of the relative wind velocity, the air in the pipe connecting the two "heads" will be affected only by gravity and centrifugal force, the centrifugal force, due to the aeroplane turning, tending to make the air flow outwards along the tube, and thereby causing a difference of pressure on the two sides of the pressure gauge, equal to

$$p = l\rho v^2 \cos\phi/\mathrm{R}, \text{ where } \begin{cases} l = \text{distance between the static heads,} \\ \rho = \text{density of the air,} \\ v = \text{aeroplane's air-speed,} \\ \phi = \text{aeroplane's actual angle of bank,} \\ \mathrm{R} = \text{radius of the turn.} \end{cases}$$

The pressures dealt with are very small, being of the order of a few millimetres of water, so that the differential pressure gauge must be very sensitive, those having a very thin rubber diaphragm being generally the most satisfactory. A want of true alignment of the heads will cause small errors in the pressures given by the "static tubes"; this is particularly the case when the aeroplane is side-slipping. The "heads" are therefore made to swivel, and have wind vanes to keep them pointing directly into the relative wind. Real differences of static pressure of the air at the two heads must affect the gauge reading, so that on "bumpy" days the reading is somewhat unsteady. "Venturi tubes" have been tried in place of "static tubes," with the object of increasing the pressure difference, in which case the action depends mainly on the relative velocities of the two wing tips through the air. They are, however, necessarily more unsteady in "bumpy" weather, which makes them inferior to "static tubes."

(ii.) *Gyro Turn Indicators.*—If a rotating gyro wheel, spinning about an axis A, be turned about another axis B, at right angles to A, it will try to precess about a third axis C, at right angles to A and B. Also, if its movements about the axis C be resisted, say, by springs, the displacement about this axis will be a measure of the rate of turn about axis B.

A gyro wheel spinning about a horizontal axis is therefore mounted in a frame which can turn about another horizontal axis at right angles to the rotor axis, and whose movements are controlled by springs. The

movement of this frame is communicated to a pointer on the instrument board. The gyro wheel may be spun electrically or by air pressure, as from the exhaust of the engine, or by suction, as from a Venturi tube exposed to the relative wind, or the actual gyro wheel may be provided with some form of vanes and itself exposed to the relative wind. In any case, it is important that the sensitiveness can be quickly changed, which is most easily effected by making the strength of the control springs adjustable. It is desirable that slow turns should easily be seen, and also that the pointer should not come to the end of its travel, except for extremely rapid turns, so that a rough idea of the rate of turn may always be obtained. It is thus advantageous to make the instrument more sensitive for slow turns than for rapid ones. To some extent the banking of the aeroplane automatically reduces the sensitiveness of these instruments for rapid turns, but they are generally designed so that the torque due to the control spring increases more rapidly

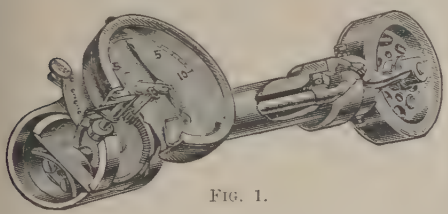


FIG. 1.

than in proportion to the deflection of the gyro frame (see *Fig.* 1).

In some instruments small coloured electric lamps are fitted, either in addition to, or in place of, the ordinary dial or pointer. Contacts are arranged so that one lamp lights up (say red) when a turn is made to the right, and the other (say green) when the aeroplane turns to the left.

This arrangement catches the pilot's eye immediately a turn begins, and so requires less careful watching than the dial and pointer.

§ (5) AIR LOG.—The air-speed indicator is a most important instrument in aircraft, for showing—like the speedometer on a motor-car—the speed at the time of observation. But, unlike the speedometer of a car, it cannot easily have a "mileage" dial added. If aircraft have to be navigated from one place to another out of sight of the ground, it is necessary that the distance flown through the air should be known. This can, of course, be found from the reading of the air-speed indicator (when corrected for density) [1] and the duration of the flight. However, such a method would be inconvenient, especially if the air-speed be not kept constant, so that an air log is required to show the actual miles flown through the air. For this purpose the air meter, or windmill type of instrument, is most convenient, as the number of revolutions are directly proportional to the distance flown (neglecting frictional effects), and having no correction for density, the instrument reads correctly at all heights. The windmill must be placed in a position where it is exposed as freely as possible to the relative wind—say an outer strut of an aeroplane; thus the number of revolutions of the windmill must be transmitted back to an indicator on the instrument board. This may be done

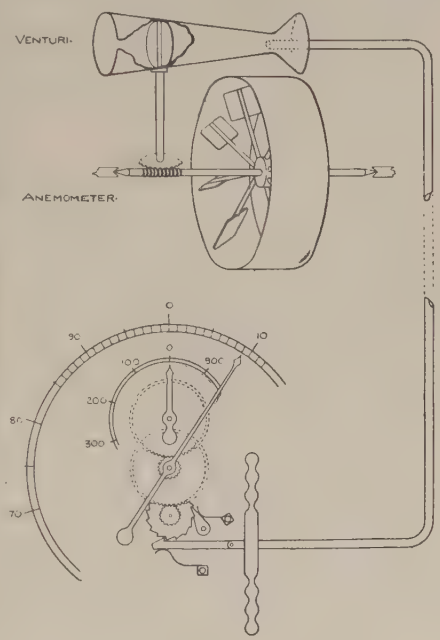


FIG. 2.

electrically, but a pneumatic system is more convenient, since it eliminates the use of batteries or other sources of current, and uses power derived directly from the relative wind. In this type of instrument (see *Fig.* 2), a Venturi tube is fixed alongside the windmill, which is a few inches in diameter, and a disc, mounted inside the exit cone of the Venturi tube, is caused to rotate about an axis in its own plane, by suitable gearing (say 500 to 1) connecting it to the windmill. A side tube is taken from the throat of the Venturi in the usual way. As the windmill turns the disc in the Venturi, the pressure in the side tube will alternate between "Pitot" pressure, when the exit cone is shut, and the "Venturi" suction, when the exit cone is open. With a good single Venturi tube, this difference of

[1] See section on "Air-speed Indicators."

pressure will be equal to that of many inches of water, at ordinary flying speeds. The side tube from the Venturi is led back to the indicator on the instrument board. The indicating mechanism consists of a diaphragm which is moved backwards and forwards by the alternating pressure, and works a ratchet which turns an ordinary counting mechanism.

Wherever the windmill be placed, the air stream past it will almost always be somewhat disturbed by neighbouring parts of the aircraft, so that it will not be exposed to the true relative wind. On aeroplanes this effect would generally make the instrument read a few per cent too low, or occasionally a little too high. As this error will be different for different machines, and different positions, some means of correction must be available which can be applied after an actual calibration in the air. This is conveniently obtained by fitting stationary vanes in front of the windmill, which can be adjusted through a small angle. These vanes impart a slight rotary motion to the air, which may increase or decrease the speed of the windmill. This system is simpler than any arrangement of variable gearing, or adjustable vanes on the windmill. In some cases the interference error is not a constant percentage of the air-speed, but the variation with change of air-speed is generally small, and will not cause an appreciable error.

Friction in the windmill and gearing will cause it to run too slow. This error may be allowed for by adding a certain mileage per unit time, independent of the actual velocity. In any case, with a good instrument the error is very small, and is quite negligible at the high speeds at which this instrument is used.

In starting to fly from one place to another by dead reckoning, the first thing that must be done is to calculate the course and distance to be flown through the air, allowing for the drift due to the wind. For this calculation the aeroplane's air-speed must be assumed, but if the actual air-speed differs a little from this, the resultant error is very small, if the calculated distance be flown through the air. Thus, if v be the assumed air-speed, and dv the difference between this and the actual air-speed, while w is the wind velocity, the vector error produced is only wdv/v^2 times the distance flown; *i.e.* since the wind velocity will generally be less than a third of the aeroplane's speed, a 10 per cent change of air-speed will cause an error of less than 3 per cent of the distance flown.

§ (6) Air-speed Indicators.—The standard means of measuring speed through the air which is now used on British aircraft is that known as the "Pressure Tube" method. A "head," consisting of two parts—the "pressure" or "Pitot" tube and the "static" tube—is fixed on some exposed part of the aircraft, where it is as much exposed to the true relative wind as possible. Pipes are led from this head to a differential pressure gauge, placed in some convenient position, whose readings indicate the air-speed.

The "pressure" or "Pitot" tube usually consists of a plain tube some $\frac{5}{8}$ inch in diameter, whose open end points directly into the relative wind. In such a tube, moving through a compressible fluid, the pressure is raised above the static pressure in the surrounding fluid by an amount equal to

$$p = \tfrac{1}{2}\rho v^2\left[1 + \tfrac{1}{4}\frac{v^2}{a^2}\right], \text{ where } \begin{cases} \rho = \text{density of the fluid,} \\ v = \text{relative velocity,} \\ a = \text{velocity of sound in the fluid.} \end{cases}$$

The effect of the compressibility of the air is represented by the term $\frac{1}{4}(v^2/a^2)$, which is negligibly small, being well under 1 per cent at the maximum air-speeds likely to be attained.

The "static" tube also consists of a tube about $\frac{3}{8}$ inch in diameter, pointing into the relative wind, but closed at its forward end, and opening by a number of holes drilled through it a few inches from the front end. The air thus blows tangentially past these holes, and the pressure within the tube is equal to the static pressure of the surrounding air, with considerable accuracy, being independent of its velocity relative to the air.

The difference of pressure between the two parts of the "head," which is measured on the pressure gauge, is therefore connected with the air-speed by the equation above. The type of "head" described above has the great advantage that it is very easily made, and small differences between two "heads" do not cause any appreciable change in the pressures. They have the further advantage that they are not very sensitive to the exact alignment of the "head" to the relative wind, as shown in the following table:

Error of Alignment.	Error in Velocity.
	Per cent.
5°	$\frac{1}{2}$
10°	$1\frac{1}{4}$
15°	3
20°	4
25°	5
30°	6

The major part of this error is due to the "static" tube, the "Pitot" tube being still less sensitive to alignment errors.

(i.) *Correction for Density of Air.*—The pressure gauges used with this instrument are usually graduated in air-speeds, which are correct for the average density at ground level

(10° C. and 760 mm. Hg.). If the density changes—as in ascending to higher levels, where the density is less—the instrument will read incorrectly, as shown by equation above. This can be accurately corrected if the pressure and temperature at the height concerned are measured. If no thermometer be carried on the aircraft, the air-speed can be corrected by using the average density at the height, as measured by a standard altimeter. In this case, since the temperature and pressure of the atmosphere may be different from the average, the corrected air-speed will have a "probable" error of about 0·6 per cent. Simple forms of slide-rule have been designed to effect the calculation easily.

(ii.) *Interference Errors.*—The adjacent parts of the aircraft will generally cause some disturbance of the relative wind at the air-speed indicator "head." In aeroplanes with the "head" fixed on a strut this generally causes the reading to be too low by a few per cent; in exceptional conditions it may be too high.

In the earlier types of air-speed indicators the "static" tube was replaced by an opening giving a definite suction, such as a cone opening backwards from the relative wind, and in some countries "Venturi" tubes are used. The disadvantage of these is, that small differences in manufacture may alter the pressure, and this is especially the case with the "Venturi" tube, where also the suction is not proportional to the square of the velocity, but to a rather higher power. The advantage of these types is that a greater pressure difference is produced, so that a less delicate pressure gauge is required. This advantage is particularly apparent at low speeds.

Instruments of the windmill variety have also been used, and have the advantage that they are independent of air density. The difficulty of transmitting the reading from the instrument, in its necessarily exposed position, to a convenient position for the pilot to see, together with the disadvantage of rapidly moving parts and the consequent wear, have prevented these instruments from being generally adopted.

§ (7) Gyroscopically controlled Rudder. —By carefully watching the compass and turn indicator, the pilot of an aeroplane can fly on a given bearing through the air with an accuracy which is easily sufficient for purposes of aerial navigation. Such a process, continued for a long time, naturally becomes very tiring. An automatic device by which the aeroplane is kept on a given course, even for a few minutes, will greatly reduce the strain on the pilot, since he need only attend to his direction once every few minutes. It is not by any means necessary that the automatic steering apparatus should be able to keep the direction *better* than can be done by personal control.

A free gyroscope, hung in frictionless gimbals, with its rotor axis horizontal, and perfectly balanced, will keep a constant direction in space. By making it slightly out of balance it can be made to precess, so that it keeps a constant direction, relative to the earth, for any given latitude. The gimbal ring pivots will not be perfectly frictionless, but the friction can be made so small that the error caused is negligible for this purpose for, say, a ten-minute run. Such a gyro may be made to work a relay, and so control the direction of the aircraft. The relay mechanism is generally electrically or pneumatically operated. Some form of "follow up gear" must be provided, so that the rudder is not thrown full over as soon as the aircraft turns a small amount. As an example of such a "follow up gear" we may take a pneumatic type of control (see *Fig.* 3). Here the gyro is

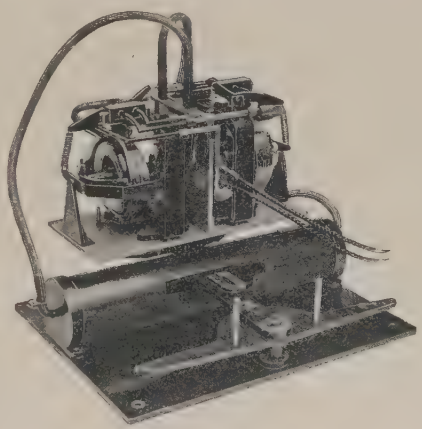


Fig. 3.

connected to the central part of a rotary valve, which, when turned, admits compressed air to one or other side of a piston working in a cylinder. This cylinder is fixed to the aircraft, and the movement of the piston both moves the rudder and rotates the outer part of the rotary valve, the movement of the piston always tending to close the valve. With this arrangement, if the whole apparatus be turned round through, say, 5°, air will constantly be supplied to one side of the piston, until it has moved the outer part of the valve round, so that the air supply is again shut off. The rudder of the aircraft is connected to the piston in such a manner that if the aircraft turn to the right the rudder is deflected so as to make it turn to the left again, and the deflection of the rudder will be proportional

to the amount the aircraft is off its course. The ratio between the angle of deflection of the rudder and the amount the aircraft is off its course, is important for the satisfactory working of the apparatus, and should be adjustable.

If an electrical method is adopted, the principle is the same: a brush on the gyroscope usually travelling between two contacts connected to a reversible electric motor, which takes the place of the piston and cylinder above; the two contacts being moved in uniformity with the rudder, a "follow up gear" is again provided.

The gyroscopes may be driven continuously, either electrically or pneumatically, or they may be spun up while held in a locked position, and used while they are spinning freely by their own inertia. The disadvantage of an electrical drive is that, in addition to the trouble of leading in the current, which is generally "three-phase," the gyros always warm up and the consequent expansion is apt to change the balance. As the balance must be very perfect, the disturbance from this cause may be very noticeable. Without very careful design the blast of air in a continuously air-driven gyroscope is liable to cause precession. The free running gyroscope avoids both these troubles, but of course gradually slows down, so that it must be re-spun periodically. This necessitates using two gyroscopes if this method of driving is employed, so that one may be controlling the aircraft, while the other is being spun up to speed.

To get good results, the rudder should respond very quickly to the relay valve, which means that in a pneumatic apparatus the valve should open wide, for very little movement of the gyro, and the air pressure should be fairly high. With good design it is possible for such gyroscopic steering apparatus to keep the path of the aeroplane straight within a degree or so for ten minutes provided the air is not very "bumpy."

If, when the gyroscope has been released, and is controlling the aircraft, it is found that the course which is being steered is slightly in error, it may be simply corrected if a control is provided which alters the relative position of the body of the valve and rudder. Release gears are provided, so that the whole gyroscopic apparatus may be disconnected from the rudder when required.

§ (8) Compasses on Aircraft.—It is unfortunate that the magnetic compass, which may be considered the primary navigation instrument, should have certain very serious defects when used on aircraft, especially as these defects are due to inherent fundamental causes, and cannot therefore be entirely overcome by any changes in design. On board ship no serious troubles arise which have not been overcome, and the instrument is generally satisfactory. The cause of the different behaviour on aircraft lies in the very different speeds of these two means of travel, and the effects we are concerned with are proportional to the square of the speed.

It should first be noted that what a compass is required to indicate is the magnetic meridian, which is a plane, defined by the direction of the total magnetic force, and the vertical, or what would serve equally well, the direction of the line formed by the projection of the direction of the total magnetic force on to a horizontal plane. It will thus be seen that the direction of the vertical is necessarily involved, as well as the direction of the total magnetic force. Now there is no method of finding the vertical which could be used, except by an ultimate reference to gravity, and the fact that accelerations prevent the true direction of gravity being found shows that errors must occur; further, considering accelerations due to turning (since other accelerations generally only last a short time and so only cause unsteadiness of the compass) as the centrifugal force depends on the square of the velocity for a given radius of turn, we see that on board ship, where the speeds are generally less than a fifth of aeroplane speeds, the disturbance of the direction of the true vertical will be less than a twenty-fifth of that on an aeroplane.

It is chiefly while flying on northerly courses that this effect is most troublesome, since it will be seen that the accelerations caused by a turn to the west will make what we may call the "apparent north" (*i.e.* the magnetic meridian found by using the apparent vertical instead of the true vertical) move to the west also. In general, at the start of a turn, the "apparent north" will travel to the west more rapidly than the aeroplane turns to the west; thus, the pilot of an aeroplane will think he has turned to the east, *i.e.* in the wrong direction. If the pilot has some means of knowing whether he is flying straight or not, so that when he desires to he may fly a straight course for some seconds without reference to the compass, then accelerations due to turning will be avoided and the compass will be perfectly reliable. This, of course, is what really happens in clear air, the pilot flying straight by means of external objects, but in a cloud there is no means of flying straight, and it is here that the trouble arises. Further, even on ordinary navigation flights, it may often be necessary to fly through some cloud, and if the pilot is unable to fly straight in the cloud, and his compass does not enable him to do so, he may easily get into a spin, from which he is unable to recover so long as he remains in cloud. It is for these reasons

that turn indicators have been introduced (see § (4)).

Previous to the introduction of the turn indicator some improvement could be made in compasses for flying in cloud by using a card with a very long period, so that they were very sluggish, only turning slowly if the direction of the magnetic force changed, consequently they always indicated the beginning of a turn in the right direction. It can be shown that for every speed there is a critical period of the compass, above which, turns off north will be shown in the right direction. This critical speed increases with increasing velocity. With the introduction of turn indicators, however, the position became entirely changed, and the compass, instead of being required to show the aeroplane's direction at all times, now need only show the average direction at certain favourable times. This calls for an entirely different design of compass for use with turn indicators to those used in the past when such instruments were not available. Thus it will probably be found that high damping, small inertia, and large magnetic moment are desirable in compasses used with turn indicators, though the reverse was largely true for compasses which had to be used in clouds without the aid of turn indicators.

§ (9) Sextants for Aircraft.—In order to determine the angular elevation (or depression) of any object, it is necessary that there should be some means of finding the true vertical. The two methods employed on the surface of the earth are, of course, the vertical, as given by a sensitive bubble level, and the horizontal, as given by the surface of the sea. For use in the air both these methods have serious disadvantages; the horizon method, because on most days the true horizon is not visible from aircraft, above a very moderate height, owing to the atmospheric haze. The objection to the bubble level method is that since the aeroplane may not be flying straight and at a uniform speed, the bubble may be subject to various accelerations, which cause the apparent direction of gravity to deviate from the true vertical.

(i.) *Haze Horizon Method.*—The problem is fortunately not quite so hopeless as might at first sight appear, when these difficulties are realised. An alternative to the true horizon is found on many days in the top of the layer of atmospheric haze, which is frequently very sharp and well defined and is usually at a height of between 3000 feet and 8000 feet. The top of this layer is very nearly horizontal, and has therefore sometimes been used as a substitute for the real horizon. The objection to this method is that although very nearly horizontal this haze horizon cannot be relied upon to give any great accuracy and may at times have a slope of a degree or more. As there is no method of knowing whether, on any given occasion, the top of the layer of haze departs much or little from the true horizontal, elevation angles determined in this way are subject to considerable uncertainty, which, of course, no increase in the number of observations will remove. The tops of layers of cloud are also frequently nearly horizontal and can be used in place of the true horizon, but have the same objection as the haze horizon. Angles of elevation may be measured from haze or cloud horizons by an ordinary marine type of sextant, but in this case the height of the aircraft above the haze must be known in order to allow for the "dip of the horizon." This can be avoided by the use of a special sextant of periscopic form in which the horizons, both in front and behind the observer, are seen in the field of view simultaneously, the rear horizon being inverted. If the observer be on the level of the top of the haze, the front and rear horizons will coincide, while if he be above it the inverted rear horizon will appear above the front horizon, while the true horizon (assuming the top of the haze to be level) will be half-way between the two. By means of an adjustable prism or mirror the image of the sun or star whose altitude is being found can also be made to appear in the field of view, and the instrument is adjusted till this image appears half-way between the two horizons.

(ii.) *Bubble Sextants.*—It is found that the determination of the vertical by means of a bubble level is capable of fair accuracy on aeroplanes or airships, provided that the atmospheric conditions are not bad and that certain precautions are taken in flying the machine. It must be remembered that the bubble, being equivalent to a short period pendulum, will indicate what is practically the instantaneous direction of "apparent gravity," *i.e.* the resultant of gravity and the acceleration of the instrument at the moment. The accidental accelerations of the aircraft must be kept as small as possible by flying at a height where the air is steady, and by steering as straight and keeping as constant a speed as possible. If the direction of "apparent gravity" does not coincide with the vertical, the bubble sextant will inevitably read incorrectly. The most that the instrument designer can really do is to make the sextant as convenient to use as possible. The main points to be noted in this connection are the following:

(1) The radius of curvature of the bubble, and the characteristics of the optical system should be so chosen that the images of the bubble and of the object appear to travel over the field together, if the whole instrument be tilted fore and aft. This greatly simplifies the use of the instrument, and as it is extremely

easy to arrange, it is very surprising that it is seldom found on ordinary clinometers, where not infrequently the images of the bubble and the object move in opposite directions when the instrument is tilted.

(2) The field of view and the travel of the bubble should be large; in actual use on aircraft the image of the sun or star and the bubble will almost always be moving up and down relative to each other, and the instrument is taken as being correctly set when they move equal distances on either side of each other. If the movement of the bubble be restricted it will constantly come up to the limit of its travel and spoil the observation.

marine type of sextant, and is seen by means of a mirror inserted in the telescope, so that both the star and the bubble appear in the field of view simultaneously. The sextant is then used in the ordinary way except that the image of the bubble replaces the horizon. A more convenient and compact type of bubble sextant can be made if the whole instrument is redesigned. Thus it is convenient for star work to look directly at the star instead of seeing it by reflection. In this type of instrument the sun or star is generally viewed directly through an adjustable clear glass mirror, and the image of the bubble as seen through a collimating lens is viewed by reflec-

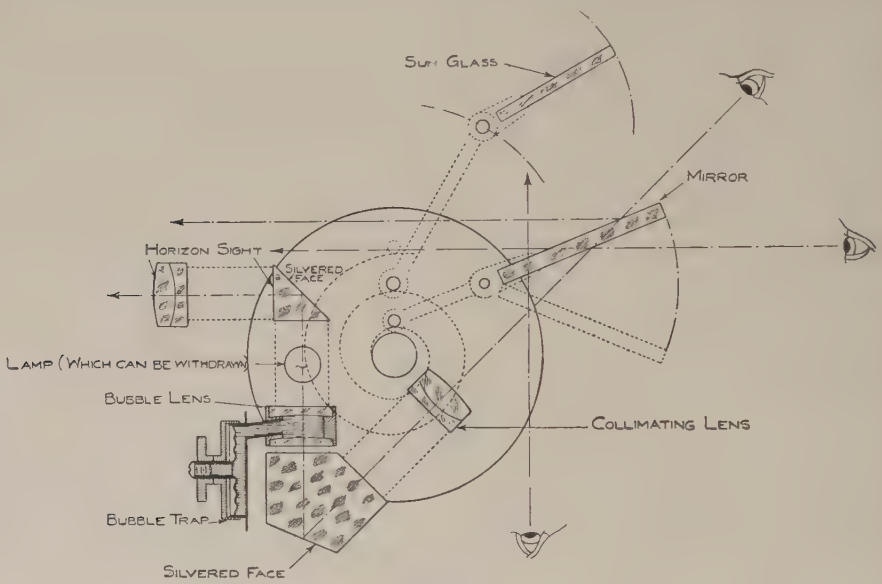


Fig. 4.

(3) Owing to the large range of temperature in which the instrument may be used, the expansion and contraction of the liquid will cause the bubble to change greatly in size, and a means of adjusting the size should be provided. This can be done by making part of the bubble container of a flexible metal diaphragm, which can be moved in or out by an adjusting screw. The container is filled with liquid, free from air, so that on expanding the diaphragm a bubble of vapour is formed, which immediately condenses again if the diaphragm be moved inwards.

(4) For star work it is desirable that the bubble should be illuminated from the side, so that it appears as a bright ring against a dark background. In any case the illumination must be easily adjustable over a very wide range.

The bubble may be placed in a side tube opening out of the telescope of an ordinary

tion in this mirror (see *Figs.* 4 and 5). By rotating the mirror, the image of the star and the bubble can be made to coincide. The same instrument can also be used by looking down on to the mirror, so that the sun or star is seen by reflection in the mirror and the bubble is seen through the mirror. The position of the mirror gives the elevation of the sun or star. The size and illumination of the bubble are adjustable, and a watch and writing tablet are attached to the instrument for convenience in recording the observations. If it may be desirable to use the real or a haze horizon occasionally, a prism and lens may be added above the bubble lens, so that the horizon is seen in the field of view as well as the bubble.

(iii.) *Gyroscopic Methods.*—The bubble sextant shows only the angular altitude of an object relative to the direction of apparent gravity at the time of the observation, and if

the instrument is subject to acceleration this will not coincide with the true vertical. If, however, the aircraft is being flown on a path which is not turning continuously to one side, the average of a large number of observations must be very near the truth. If in place of the short period bubble a gyroscope having but slight gravity control be used, this will pick up approximately the mean direction of apparent gravity, and a result will be obtained which is analogous to the mean of a number of observations with the bubble sextant.

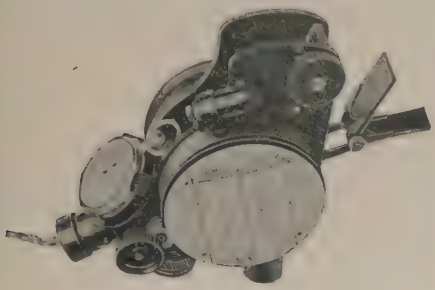


FIG. 5.

The gyroscopic method has one rather serious disadvantage, namely, that since the direction given by the gyroscope changes only slowly, readings taken at a small interval of time will be by no means "independent," and the accuracy cannot therefore be greatly improved by taking a number of observations unless they are spread over a long interval of time, which is generally inconvenient. With the bubble sextant all the observations are "independent," so that the statistical improvement will be obtained by taking the mean of a number of observations, and the dispersion of the group gives a measure of the accuracy of the mean. G. M. B. D.

AIRCRAFT, PERFORMANCE OF

THE PREDICTION AND ANALYSIS OF THE RESULTS OF OBSERVATION

§ (1) INTRODUCTION.—The earliest attempts to predict the possibilities of flight date back many centuries, but did not lead to any demonstrations until the end of the nineteenth. The last century, however, saw a quickening of the pace, and some of the early attempts of Stringfellow and Henson to interpret the most advanced thought of the middle of the nineteenth century approached modern ideas of aviation to a surprising extent, except for the motive power. In all these early investigations it is clear that inspiration came from bird life, and engineering considerations alone have gradually driven later workers away from that prototype. The history of the subject in these early days has been written by the Royal Aeronautical Society,[1] and, apart from the interest of the subject-matter, shows how the development of ideas from their inception to application may depend on some revolutionary development not contemplated in the original investigations. In flying, the change was produced by the invention of the light petrol motor, which in turn evolved from the heavier internal combustion engines of fifty years ago.

It is probably not unfair to date the beginning of the modern phase of flying to the neighbourhood of the years 1890–1900, and to give a foremost place to the researches of Langley. As a result of experiments which he made on a whirling arm on the lifting possibilities of flat plates, numerous enthusiasts made predictions of the capabilities of flying machines. They concluded, quite correctly, that twenty or thirty horse-power would suffice to carry a man at a speed of over thirty miles per hour if the engine and structure could be provided within a total weight of 600 lbs. The area of the lifting surfaces under the circumstances would be nearly 1500 sq. ft. Some fifteen or twenty years after the realisation of these quantities the invention of the petrol motor brought the possibilities within those of engineering limitations, and in 1908 public flights of an hour and more in heavier-than-air craft marked the end of the long period of uncertain development.

The achievements up to this time which formed milestones were the freely flying models of Langley, in which of course manual control was out of the question, and the huge machine of Maxim which showed a force of 10,000 lbs. produced by lifting planes and air-screws. The areas of lifting surfaces per unit weight were then generous as compared with modern ideas, being some three times as great as at present. Also with improvement of knowledge it has been found possible to economise in power. The history of the period 1908–1920 has been one of very rapid development of ground partly cleared by these earlier achievements, by a largely increased number of individuals working to that end. The greatest stimulus came from the Great War, and from a number of aeroplanes in 1908 which could be counted on one's fingers, British production passed to nearly 1000 per week in the concluding months of 1918. The performance of heavier-than-air craft at the close of the war varied greatly: the fast aeroplane was a single-seater weighing something less than 2000 lbs., fitted with an engine of about 300 horse-power. The least speed of sustained flight (somewhat less than that for efficient landing) was 45 to 50 m.p.h., and the highest speed upwards of 140 m.p.h.

[1] *Aeronautical Classics.*

Between the two there is a certain amount of interchange by which both minimum and maximum speeds increase or decrease together, and the final choice depends on the lower, and this again on the state of perfection of the landing grounds. The rate of climb of these fast aircraft exceeds 2000 ft. per minute near the ground, and a height of 10,000 ft. can be reached in less than ten minutes. The fighting in the air which became a prominent part of warfare often took place at altitudes of 15,000 ft. to 18,000 ft., and in the rarefied atmosphere the conditions of flight were very different from those near the ground. In particular the engine develops far less power and, apart from the question of breathing of the pilot, is the main factor in settling the height to which an aeroplane can climb. This height has already been pushed to more than 30,000 ft.

At the other end of the scale of modern aeroplane is the weight carrier. The extreme of gross weight flown is about 30,000 lbs. and a horse-power of 1500 is provided. Speed is not the main objective, and 85 to 90 m.p.h. is definitely designed for, in order that the net lifting power may be as great as possible. For short flights of a hundred miles or so the net load may be more than 40 per cent of the gross load, but owing to the weight of fuel for a non-stop flight the net load on an Atlantic flight is very small indeed. For commercial purposes, therefore, it has become usual to limit the stages of flight to 300-400 miles, a distance which is also indicated by the endurance of the pilot. Large aeroplanes bring very appreciable extra duties to the pilot, and the provision of assistance for him is one of the current problems.

The seaplanes best known to us correspond in performance to the weight-carrying aeroplanes. The best have boat-shaped hulls which allow them to rest or ride on the water, and in addition to the performance in the air introduce problems relating to performance on the water. The latter are dealt with by the apparatus and methods used in naval architecture in the design of steamship hulls.

Airships and lighter-than-air craft such as kite balloons have developed rapidly in the same period as the aeroplane. The problems involved are different, for an airship can lift without being in forward motion and may hover over a given spot. The largest are rigid airships having a gross lift of 60 or 70 tons and a speed upwards of 60 m.p.h. The smaller class may weigh about one-quarter of this, and the envelopes are maintained to shape by a sufficiently high pressure inside a cover of flexible fabric. Their performance in speed is little different from that of their larger sisters, but the range in miles is less.

§ (2) Prediction of Performance.—The word performance has come to have a technical meaning, and by it is usually understood the speed of horizontal travel for aircraft in general, the height to which they can climb, and, in the case of the aeroplane, the rate of climb. It does not cover the statement of the lightness or otherwise of the controls or the conditions as to stability.

(i.) *The Standard Atmosphere.*—The general theory of performance covers all types of aircraft whether heavier or lighter than air, and depends on a basis which is universally adopted and not open to serious criticism on physical grounds. The calculations are made for a standard atmosphere which in Britain is defined by the following table. There are small but relatively unimportant changes on the Continent, and it is probable that an early attempt will be made to produce an agreed international basis. The table given may be taken to represent the average conditions which prevail in the atmosphere, and one of the problems met with in analysis of performance is that of converting observations in a non-standard atmosphere to those which would have been made had the atmospheric conditions been standard.

Table I.—Standard Atmosphere

Standard Height.	Relative Density.	Relative Pressure.	Temperature.	Absolute Temperature.	Aneroid Height.
(ft.).	σ.	p.	° C.	° C.	(ft.).
0	1·025	1·000	9	282	0
1,000	·994	·964	7·5	280·5	1,000
2,000	·963	·929	6	279	2,010
3,000	·932	·895	4·5	277·5	3,020
4,000	·903	·861	3	276	4,040
5,000	·874	·829	1·5	274·5	5,070
6,000	·845	·798	0	273	6,100
7,000	·818	·768	−1·5	271·5	7,130
8,000	·792	·739	−3	270	8,180
9,000	·765	·711	−4·5	268·5	9,230
10,000	·740	·684	−6	267	10,290
11,000	·717	·658	−8	265	11,360
12,000	·695	·632	−10	263	12,440
13,000	·673	·607	−12	261	13,520
14,000	·652	·583	−14	259	14,600
15,000	·630	·560	−16	257	15,700
16,000	·610	·538	−18	255	16,800
17,000	·590	·516	−20	253	17,900
18,000	·571	·496	−22	251	19,010
19,000	·553	·476	−24	249	20,140
20,000	·535	·456	−26	247	21,270
21,000	·515	·437	−28	245	22,410
22,000	·498	·419	−29·5	243·5	23,560
23,000	·481	·402	−31·5	241·5	24,720
24,000	·464	·385	−33	240	25,890
25,000	·448	·369	−35	238	27,060
26,000	·432	·353	−37	236	28,240
27,000	·417	·338	−38·5	234·5	29,430
28,000	·402	·324	−40·5	232·5	30,640
29,000	·388	·310	−42	231	31,860
30,000	·374	·296	−44	229	33,100

The table needs little explanation. The atmosphere is taken to have unit density when the temperature is 15·6° C. (60° F.) and the pressure 760 mm. of mercury, and the relative densities and pressures tabulated are based on this standard. The choice of this basis is somewhat arbitrary but is convenient as being that adopted by the aerodynamics laboratories of the world, and so allows of direct use of the data obtained there: that is, the quantities tabulated in lbs.-force, etc., for a given wind velocity are strictly correct when the air has the pressure and density adopted as standard. The air-speed indicator of an aeroplane shows real speed when the density is unity, *i.e.* at a height of nearly 1000 ft. At 20,000 ft. the reading must be increased in the ratio 1·37 : 1 to give real speed.

The final column of the table is peculiar to aeronautics and arises from the use of an aneroid barometer which is marked with a scale of feet instead of divisions in inches or millimetres of mercury. An aviator knows his height approximately from this reading, but a comparison of the first and last columns will show that the differences from real height become important[1] at 10,000 ft. and greater altitudes. For the purposes of prediction and analysis the aneroid barometer is regarded solely as a pressure indicator and aneroid height then gives a reading of pressure by means of the formula[2]

$$h = -62{,}700 \log_{10} \mathrm{P} \quad . \quad . \quad (1)$$

or its equivalent, the third and sixth columns of the table, where P is the ratio of the pressure to that at ground level.

In flight, the quantities observed—pressure by the aneroid barometer, and temperature by a thermometer on one of the wing struts—suffice to determine density and thence standard height by use of Table I. Owing to the special choice of units the relation between P, t, and σ is

$$\sigma = \frac{288{\cdot}6}{273+t}\mathrm{P}. \quad . \quad . \quad . \quad (2)$$

Observations of P and t are sufficient to define the atmosphere for aeronautical purposes.

(ii.) *Aeronautical Properties of the Aeroplane required for Prediction and Analysis.*—The aeroplane is regarded as a combination of two rigid bodies, the wings, fuselage, and undercarriage being one and the air-screw the other; the parts can have a relative motion of rotation which is governed by the power of the engine and the position of the engine controls. For a rigid body moving through the air it is known that the forces acting depend on the speed and shape of the body in marked degree, are proportional to the density, and are dependent on the viscosity of the air. Included in the shape of the body is the idea of attitude of presentation by which a wing at one angle of incidence is regarded as a different body from the same wing at any other angle of incidence. From the idea of shape is definitely excluded the scale, and a model aeroplane is said to be of the same shape as the aeroplane itself.

§ (3) Aeroplane Glider. *Lift and Drag.*—If the velocity of the body be considerably less than that of sound in the fluid, the equation[3]

$$\mathrm{R} = \rho \mathrm{V}^2 l^2 f\left(\frac{\mathrm{V}l}{\nu}\right) \quad . \quad . \quad . \quad (3)$$

expresses the experimental knowledge of the subject in the most general form consistent with the principles of dynamical similarity. In this expression R is the air force on a body moving with velocity V; the shape and presentation are defined by the function f and the scale by l. The density of the air (mass per unit volume) is denoted by ρ and the kinematic viscosity by ν. So long as the dimensions of the various quantities are dynamically self-consistent, equation (3) is independent of the units involved and is such that $f(\mathrm{V}l/\nu)$ is of no dimensions. The form of the function f can only be determined experimentally in the great majority of instances of motion.

It is known that f is approximately constant for large changes in the variable $\mathrm{V}l/\nu$, and the assumption is always made that the range of flying speeds is covered sufficiently accurately by the assumption of constancy, and for the aeroplane

$$\mathrm{R} = k_{\mathrm{R}} \rho \mathrm{V}^2 l^2, \quad . \quad . \quad . \quad (4)$$

where k_{R} is a non-dimensional coefficient to be determined experimentally. With the resolution of forces into lift and drag are introduced corresponding coefficients such that

$$\mathrm{L} = k_{\mathrm{L}} \rho \mathrm{V}^2 l^2 \text{ and } \mathrm{D} = k_{\mathrm{D}} \rho \mathrm{V}^2 l^2, \quad . \quad (5)$$

and tables of k_{L} and k_{D} are to be found in the publications of the aerodynamic laboratories.[4]

§ (4) Air-screw.—Two changes are introduced into the form of (3) as a result of theoretical and practical considerations of the action of an air-screw. The tip speed of an air-screw may exceed 600 ft. per second and then, as was pointed out by Lord Rayleigh,[5]

[1] It is understood that a new marking of aneroids is coming into use which will reduce this difference. This will affect column 6 of the table, but the principles of the reduction remain the same.

[2] See "Barometers and Manometers," § (16) (iii.), Vol. III. The figure 62,700 is based on the value 0·00237 g lbs. per c. ft. as the density of air at 288°·6 abs. (15°·6 C.), and 32·2 ft. sec.^{2} for g leading to 0·0763 lbs. per c. ft. Compare the figure 62,759 of Airy's Table.

[3] *Advisory Committee for Aeronautics*, 1909–10, p. 38. See also "Dynamical Similarity," § (14), Vol. I., and "Aircraft Model Experiments in relation to Full Scale"

[4] *Advisory Committee for Aeronautics.* Report of Scale Effect Sub-Comm.

[5] *Advisory Committee for Aeronautics*, 1910–11, p. 26.

it is not *a priori* permissible to regard air as sensibly incompressible. The effect can be expressed in a consistent dynamical equation by introducing a further variable V/a into equation (3) to make it become

$$R = \rho V^2 l^2 f_1\left(\frac{Vl}{\nu} \cdot \frac{V}{a}\right), \quad . \quad . \quad (6)$$

where a is the velocity of sound in undisturbed air. The range of variation of V/a under flight conditions is small, and it is assumed that even under extreme conditions f_1 may be regarded as constant in the prediction and analysis of aircraft performance. This should not be taken to mean that the effect of V/a is not appreciable over a wider range, and it is known that when the tip speed exceeds the velocity of sound in air, the assumption of constancy of f_1 breaks down completely. There is considerable evidence from gunnery experiments that (6) still continues to hold.

For aeronautical purposes, therefore, it is assumed that an equation of the form of (4) holds with the desirable accuracy. A change of form is, however, made which has important consequences in prediction and analysis. Owing to its rotation the attitude of the parts of an air-screw may change in a different way from that of the parts of an aeroplane glider. A little consideration will show that the geometry of the motion is not changed if the speed of rotation and of advance of the airscrew increase in proportion. In accordance with the laws of dynamical similarity it is found that part of the idea of attitude can be covered by a factor $f_2(V/nl)$, where n represents rotational speed, V forward speed, and l the scale of the air-screw. This leads to the equation

$$R_{\text{air-screw}} = \rho V^2 l^2 f_2\left(\frac{V}{nl}\right) \quad . \quad . \quad (7)$$

or

$$R = \rho n^2 l^4 f_3\left(\frac{V}{nl}\right), \quad . \quad . \quad . \quad (8)$$

where R stands for a force. If we identify R with thrust and put D for the diameter of the air-screw, then it is usual to write

$$T \equiv \text{thrust} = k_T \rho n^2 D^4, \quad . \quad . \quad (9)$$

and in a similar way

$$Q \equiv \text{torque} = k_Q \rho n^2 D^5, \quad . \quad . \quad (10)$$

where, from the comparison of (9) with (8), it will be seen that k_T is a function of V/nD but has no dimensions. Values will be found tabulated as the result of experiment.[1]

(i.) *Interaction of Air-screw and Aeroplane Glider Characteristics.*—An air-screw produces a thrust by dynamical means, and one of the consequences of its use is a blast of air over parts of the aeroplane glider which produces an appreciable increase in resistance. The aeroplane body has an effect on the air-screw of much smaller amount, generally in the direction of increased efficiency and increase of experimental mean pitch. It then follows that theoretically the resistance of an aeroplane will depend on V/nD, whilst the performance of the air-screw will depend on the angle of incidence of the aeroplane. It is possible to include these effects without serious addition to the difficulties of the theory of the prediction and analysis of aeroplane performance.

§ (5) ENGINE. (i.) *Torque and Speed.*—The torque absorbed by the air-screw is equal to that given by the engine, and the speed of rotation increases until a balance is obtained. The combination is very stable, for the torque of the air-screw increases rapidly with speed of rotation at constant air speed whilst that of the engine varies little. It is usual to give a curve of engine power with speed when the engine is developing maximum power and to use this in analysis and prediction. No reliance is placed on curves obtained under other conditions of the engine control as no means is known of interpreting the results.

(ii.) *Variation of Power with Height.*—The power developed by an engine for the best conditions of running decreases more rapidly than the density of the air in the induction pipe. Arrangements have been tried for making this density greater than that of the external atmosphere and lead to a supercharged engine. In the general case, therefore, the law of variation of power with height will be very variable and will need to be based on experiments either in a high altitude test-house or on some mountain peak. If no supercharging devices are used the density of the air in the induction pipe is sensibly that of the atmosphere. It is probable that the variation of power is dependent both on density and temperature, although the amount of the difference due to temperature is small. Most of the analysis which exists at the moment (1923) assumes that the variation is a function of density only. Certain simplifications of the method of reducing observations result from this assumption, which is scarcely less accurate than the observations themselves.

The quantities described above represent those of importance in the modern theory of prediction and analysis. There are others of which account cannot readily be taken. Up currents in the atmosphere will clearly increase the observed rate of climb of an aeroplane, and a similar effect may be produced by a steep gradient in the velocity of a horizontal wind. The latter effect can be found, if big enough, by flights in opposite directions

[1] *Advisory Committee for Aeronautics*, 1914–15, pp. 265-273.

over the same area, and this means of eliminating some sources of uncertainty is generally adopted. As speeds are estimated relative to the ground in many instances it is necessary to evaluate the wind speed either directly or indirectly and correct for it. In the case of the engine it is necessary to assume that the mechanical condition is that under which the power was determined on the bench and that the pilot is doing his best to maintain maximum power. The indicator for this purpose is the revolution counter, and at a constant forward speed maximum power corresponds with maximum revolutions.

§ (6) Theory of Prediction and Analysis. (i.) *General.*—The connection of the aerodynamics of the aeroplane glider and air-screw with the power characteristics of the engine constitutes the theory of prediction. The separate items are generally represented by curves such as those in *Fig.* 1 (*a*), (*b*), (*c*), and (*d*), and are wholly experimental. It is convenient to define the scale l of equation 3 as the square root of the area of the wings, *i.e.* $\sqrt{S}$; further, since the diameter of the air-screw changes with the scale it will be desirable to maintain the ratio D^2/S constant in developing the main ideas, *i.e.* to associate a definite air-screw with a prescribed aeroplane.

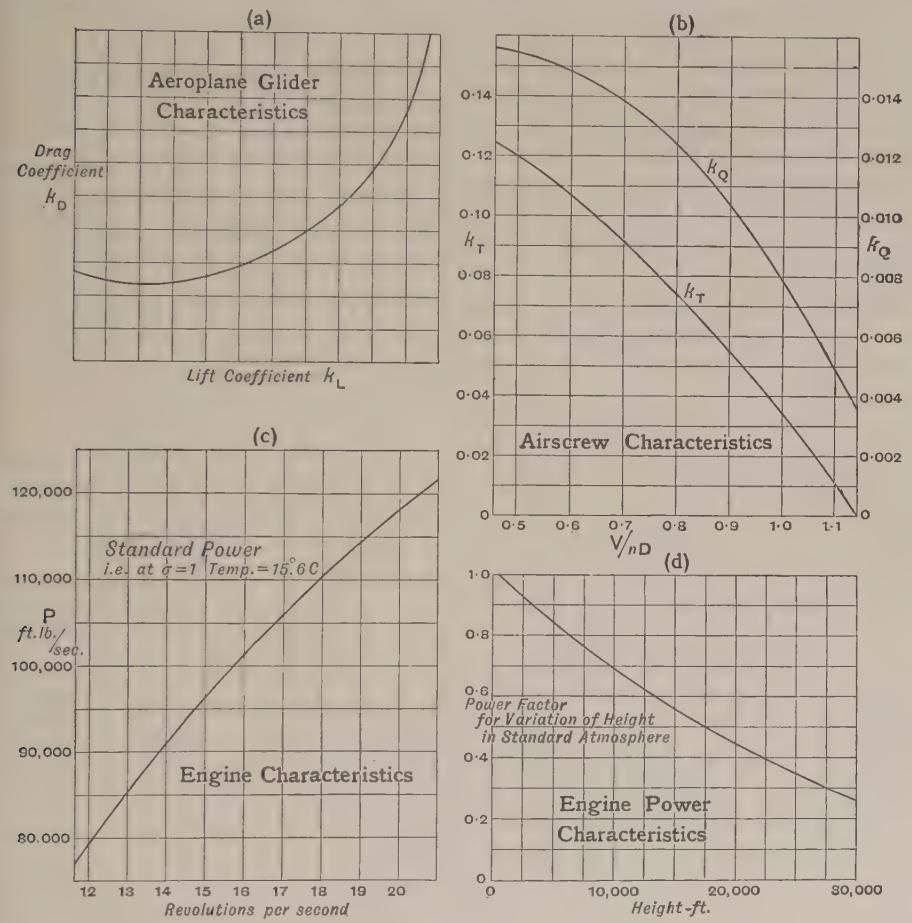


Fig. 1.

It has already been pointed out in connection with equation (3) that the resistance of an aeroplane glider depends not only on its form but on its attitude. It is only with straight flying that "performance" is concerned, and attitude then means angle of inclination to the relative wind; this fact is of present importance. Equation (3) with the modification suggested as arising from the air-screw now appears in the form

$$R=\rho V^2 S.f\left(a,\frac{V}{nD}\right), \quad . \quad . \quad (11)$$

where f depends only on the geometry of the aeroplane and is known experimentally, α is the angle of incidence, and V/nD represents the attitude of the air-screw. R may be identified with the resultant force on the aeroplane including its air-screw, and in steady flight will be equal to the weight of the aeroplane and be vertical in direction.

A complementary expression to (11) gives the inclination of the resultant force R to the direction of motion of the aeroplane through the air. Denoting the angle between the direction of R and the normal to the motion by γ, it follows from the theory of dimensions that

$$\gamma = F\left(\alpha, \frac{V}{nD}\right) \quad . \quad . \quad . \quad (12)$$

is the most general expression consistent with the preceding basis of the theory. Since in steady flight the resultant is vertical the angle γ must be equal to the inclination of the flight path to the horizontal, an angle which is denoted by θ. Conditions satisfied in the steady flight of an aeroplane are then

$$R = W, \quad \gamma = \theta. \quad . \quad . \quad . \quad (13)$$

(ii.) *Level Flights.*—In level flight θ is zero and equations (11) and (12) become

$$\left.\begin{aligned} \frac{W}{\rho V^2 S} &= f\left(\alpha, \frac{V}{nD}\right) \\ 0 &= F\left(\alpha, \frac{V}{nD}\right) \end{aligned}\right\}; \quad . \quad . \quad (14)$$

f and F being known experimentally, whilst α and V/nD are regarded as unknowns, it will be seen from the second equation of (14) that V/nD becomes a function of angle of incidence. Using this result, the first equation then shows that the expression

$$\frac{W}{\rho V^2 S}_{\text{level flight}}$$ is a function of the angle of incidence.

This is a most important result. It shows that for a given aeroplane the angle of incidence is determined by the loading per unit area ($W/S \equiv w$) and the square of the indicated air speed; ($\sigma^{\frac{1}{2}}V$ is known technically as indicated air speed and is the reading shown on the instrument usually provided in an aeroplane or airship). If W does not vary greatly owing to consumption of fuel, w is sensibly constant, and it then follows that a pilot keeps his angle of incidence constant at all heights by keeping his air speed constant. As the control and stability of the aircraft depend primarily on angle of incidence, this property of the air-speed indicator is a valuable one. Except that the engine must be able to turn the air-screw at the required value of V/nD, consideration of power does not enter into the relation.

(iii.) *Climbing Flight.*—Equations (11) and (12) now lead to

$$\left.\begin{aligned} \frac{W}{\rho V^2 S} &= f\left(\alpha, \frac{V}{nD}\right) \\ \theta &= F\left(\alpha, \frac{V}{nD}\right) \end{aligned}\right\}, \quad . \quad . \quad (15)$$

and the relation between angle of incidence and advance per revolution of the air-screw (V/n) depends on the angle of climb, which latter clearly depends on the power which is available for the purpose of climbing. For each position of the engine controls there is a different value of θ, and, regarding V/nD as an independent variable, it will be seen that for each angle of incidence, α, there is a series of values of θ which ranges from a climb with the engine fully on to descent with the engine stopped. To interpret the result a little more closely, it may be remarked that the dependence of f on V/nD is small and that $W/\rho V^2 S$ is approximately a function of angle of incidence only. At any level in the atmosphere whatever, therefore, it will be noticed that—apart from variations of W—the angle of incidence α is determined by air speed as the most important item, and (15) then shows that at a given angle of incidence the effect of increasing the power delivered by the engine is not an increase of speed but a change of inclination of the flight path to the horizontal.

With this range of solutions of (15) performance is little concerned, and that solution which makes the rate of climb a maximum is the one with which the expression "rate of climb" is usually associated. This is not quite equivalent to making θ a maximum, for the rate of climb is $V \sin\theta$, and V depends on θ if the engine is developing full power. The maximum rate of climb occurs for an angle θ rather less than its maximum value.

The engine power must balance the power absorbed by the air-screw, and hence the equation

$$\text{Power} \equiv P = \rho n^3 D^5 \psi\left(\alpha, \frac{V}{nD}\right) \quad . \quad . \quad (16)$$

follows, for the power is measured[1] by the product of rotational velocity and air-screw torque. In this expression $\psi(\alpha, V/nD)$ is written for the k_q (cf. § (14)). By a rearrangement of terms it may be found that

$$P = \left(\frac{nD}{V}\right)^3 \cdot \frac{D^2}{S} \cdot \frac{(\rho V^2 S)^{\frac{3}{2}}}{(\rho S)^{\frac{1}{2}}} \cdot \psi\left(\alpha, \frac{V}{nD}\right), \quad (17)$$

an expression which can be seen to be equivalent to (16) if the terms be collected. The ratio D^2 to S is constant as part of the geometry of the aeroplane, whilst the first factor on the right-hand side modifies the dependence of the expression on V/nD without any essential change in the mathematical form. Equation (17) may then be written as

$$P = \frac{(\rho V^2 S)^{\frac{3}{2}}}{(\rho S)^{\frac{1}{2}}} \psi_1\left(\alpha, \frac{V}{nD}\right), \quad . \quad . \quad (18)$$

the change from ψ to ψ_1 covering the constant multiplier and the factor $(nD/V)^3$.

From (14) it is readily deduced that

$$\rho V^2 S = \frac{W}{f\left(\alpha, \frac{V}{nD}\right)}, \quad . \quad . \quad . \quad (19)$$

and with suitable use of this and a change from ψ_1 to ψ_2 equation (18) takes the final form

$$\frac{P}{W}\sqrt{\frac{\rho}{w}} = \psi_2\left(\alpha, \frac{V}{nD}\right). \quad . \quad . \quad (20)$$

[1] See also "Airscrew, The," § (14).

Without any approximations other than those introduced in the formulation of the bases of the theory, it has been found that the horse-power per unit weight multiplied by the square root of the ratio of air density to the loading of the wings per unit area is a function of angle of incidence of the wings and of the ratio of the advance per revolution of the air-screw to its diameter. It is not necessary that the engine be working at full power in order that (20) may hold, for the relation is essentially deduced from the aerodynamics of the air-screw and aeroplane glider.

Without loss of generality, either of the equations in (15) may be replaced by (20) in any theory of aeroplane performance; the change has an advantage in that the variables $W/\rho V^2S$ and $P/W\sqrt{\rho/w}$ are intimately connected with ideas obtained from experience. The rate of climb, V_c, which is readily deduced from (15), is there seen to be a function of α and V/nD and now as an alternative may be expressed as a function of $W/\rho V^2S$ and $P/W\sqrt{\rho/w}$.

Thus the formulae of prediction and analysis of aeroplane performance in final form may be given as

$$\frac{W}{\rho V^2 S} = f\left(\alpha, \frac{V}{nD}\right) = f_1\left(\frac{P}{W}\sqrt{\frac{\rho}{w}}, \frac{V}{nD}\right), \quad (21)$$

$$V_c\sqrt{\frac{\rho}{w}} = F_1\left\{\frac{W}{\rho V^2 S}, \frac{P}{W}\sqrt{\frac{\rho}{w}}\right\}. \quad (22)$$

An examination of equations (21) and (22) will show that the number of independent variables to be considered is two only. It should be noted that the equations do not ensure equilibrium but only define certain consequences of it.

In using (21) and (22) the assumption is made in practice that $V_c\sqrt{\rho/w}$ is a maximum and this in effect makes $(P/W)\sqrt{\rho/w}$ the only important independent variable. Results of a test may then be shown by plotting $V\sqrt{\rho/w}$, $V_c\sqrt{\rho/w}$, and V/nD as ordinates of curves on a base of $P/W\sqrt{\rho/w}$. For an aeroplane a typical diagram is given in *Fig.* 2.

§ (7) Uses of Equations (21) and (22) which do not involve a Knowledge of the Forms of the Functions f and F.—In general, the application of the theory of prediction starts from an experimental determination of the functions f and F of equations (11) and (12), but an examination of equations (21) and (22) shows that certain problems can be solved without any direct reference to the angle of presentation α. It will be clear after very little consideration that equations (21) and (22) apply to all variations of atmospheric conditions and to such changes in the aeroplane as do not affect its external form. As instances of the latter may be given the change of engine without change of air-screw and the change of the load carried in the aeroplane. There is, however, one criterion to be applied which is not wholly covered by the equations, for it may happen that under new conditions for which aerodynamic requirements are satisfied the engine is insufficiently powerful to drive the air-screw at the necessary speed. So long as there is reserve engine power, the relations shown by (21) and (22) or the curves of *Fig.* 2 give complete information of the performance of an aeroplane in any atmosphere whatever and for any load carried so long as the changes of load are made inside the aeroplane.

It has already been remarked that curves

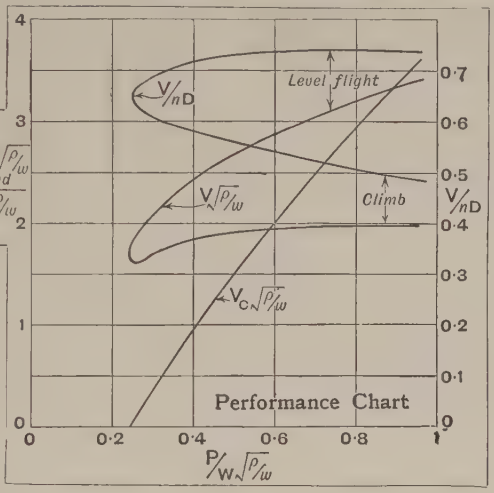


Fig. 2.

$P \equiv$ power. Unit power = unit force at unit velocity.

$\frac{V}{nD} \equiv$ advance per revolution of air-screw as a fraction of its diameter.

$V \equiv$ velocity of flight. $\rho =$ air density.

$V_c \equiv$ velocity of climb. $w =$ wing loading per unit area $= W/S$.

With the above definitions the numbers in the chart apply to any self-consistent set of dynamical units of mass, length, and time.

are found experimentally which express the power of an engine in terms of revolutions, there being a doubly infinite series of such curves each member of which corresponds with some specified density and temperature of the atmosphere. Hence the value of $(P/W)\sqrt{\rho/w}$ can be found as a function of the revolutions of the engine and the known characteristics of the atmosphere corresponding with the conditions of a new problem. If the flights be level flights, it follows from (21) and (22) that $(P/W)\sqrt{\rho/w}$ must be a definite function of V/nD in order to satisfy aerodynamic requirements. Also for the same condition of level flight it has been seen that $V\sqrt{\rho/w}$ is a function of the variable $(P/W)\sqrt{\rho/w}$, and hence from the aerodynamic

side of the problem is obtained a second relation between $(P/W)\sqrt{\rho/w}$ and n. The result of the analysis is then to show two independent relations between the quantities; there is one particular value of n which simultaneously satisfies both the requirements of the engine and air-screw. The solution of the simultaneous equations is usually carried out graphically, and it is at once obvious that a degree of mathematical accuracy of solution can be attained which is high compared with the experimental data to which it is applied.

If, then, to the curves of *Fig.* 2 be added curves of engine power as dependent on revolutions, density, and temperature, it is possible to predict the maximum horizontal speed of an aeroplane at any part of an atmosphere, standard or otherwise, for any variations of internal load.

For the purposes of simplicity of use, it has been customary to express results in terms of speed in a standard atmosphere, and so obtain results which are independent of accidental meteorological conditions. This method of presentation of results shows the overall efficiency of an aeroplane and engine in a form suitable for an estimate of its military or commercial value. If in addition diagrams such as *Fig.* 2 be prepared, a direct comparison of the aerodynamic merits is obtained by superposition, that aeroplane being most satisfactorily designed which gives the highest value of $V\sqrt{\rho/w}$ for a given value of $(P/W)\sqrt{\rho/w}$. By the use of both criterions it is possible to subdivide the relative performances of two aeroplanes and to assess quantitatively the proportions of their differences which arise from change of engine power, change of total weight, and difference of aerodynamic design.

For the rate of climb the conditions are a little more complex. The quantity required depends on the speed of flight as an arbitrary variable, that is, for the initial condition that the engine is developing its maximum power for the particular conditions of flight, there is an infinite series of values for the rate of climb which depends on the choice of flight speed. From this series is extracted as of special interest that rate of climb which is a maximum for variation of flight speed under given atmospheric conditions. In terms of the generalised variables here used, it is desired to choose $V\sqrt{\rho/w}$ or $W/\rho V^2 S$ so that $V_c\sqrt{\rho/w}$ has its maximum value.

If we write (22) in the form

$$V_c\sqrt{\frac{\rho}{w}}=F_2\left\{V\sqrt{\frac{\rho}{w}},\ \frac{P}{W}\sqrt{\frac{\rho}{w}}\right\}, \quad . \quad (23)$$

and differentiate with respect to V (keeping $\sqrt{\rho/w}$ constant during the operation), the condition to be satisfied is

$$\frac{\partial V_c}{\partial V}=0. \quad . \quad . \quad . \quad . \quad (24)$$

This may equally well be written as

$$\frac{\partial V_c\sqrt{\frac{\rho}{w}}}{\partial V\sqrt{\frac{\rho}{w}}}=0, \quad . \quad . \quad . \quad (25)$$

since $\sqrt{\rho/w}$ is constant by assumption during the partial differentiation. Applying this to (23) shows that for the conditions of maximum rate of climb $V\sqrt{\rho/w}$ is still a function of $(P/W)\sqrt{\rho/w}$ and hence the conclusions arrived at for level flight as to the use of equations (21) and (22) or *Fig.* 1 are valid in relation to the maximum rate of climb.

The conditions of comparison may be generalised by observing that (23) may be changed to

$$\frac{V_c\sqrt{\frac{\rho}{w}}}{V\sqrt{\frac{\rho}{w}}}=\sin\theta=F_3\left\{V\sqrt{\frac{\rho}{w}},\ \frac{P}{W}\sqrt{\frac{\rho}{w}}\right\}, \quad (26)$$

and it is then clear that for a constant angle of climb θ the variable $V\sqrt{\rho/w}$ remains a function of $(P/W)\sqrt{\rho/w}$ for all independent variations of V, ρ, and w. If then in the trials of an aeroplane, experiments were made to determine rates of climb other than the maximum and zero, other curves could be added to *Fig.* 2 and so render possible the prediction of flight under any circumstances to which the aeroplane may be subjected by variations of engine throttle or elevator position. This extension of the possibilities of recording the performances of aircraft is rarely carried out owing to its little value in normal use. In a few cases the equivalent tests have been made for research purposes.

It has further been usual in the reduction of British performance results to assume that the horse-power of an engine is a function of density only. This approximation was justifiable in view of the state of knowledge existing in 1918, and although there is now evidence to show that a distinct temperature effect exists, it is also clear that the changes introduced by the new knowledge are of a secondary order. The calculations which convert an observed performance into performance in a standard atmosphere are greatly simplified by the neglect of a temperature effect, for both the aerodynamics and engine power then depend only on the single atmospheric characteristic, density. The observed speed and rate of climb need only be ascribed to a height in the standard atmosphere where the density is that recorded in observation for the necessary reduction to be made.

For reasons connected with alighting there has been a tendency to the stereotyping of aircraft of a given class. Apart from this consideration, an application of the preceding formulae shows that economy of use of aircraft as a means of transport demands

large values of w or, alternatively, low values of ρ.

§ (8) Prediction from Experimental Data.—The values of the functions f and F of equations (11) and (12) or their equivalents are here necessary. It is usual to work with the components of the resultant air force which lie along the direction of motion of the aircraft (drag) and normal to it (lift) rather than with the magnitude and direction of the resultant. The lift and drag of a complete model aeroplane glider may be determined in a wind channel or the various approximate theorems in addition may be used. It has been found that a division of the resistance may be made, one part depending on the wings and the other on the rest of the aeroplane, generally known as the "body" in this connection. The body resistance itself may be subdivided, but in general the result for each part gives a value which varies as the square of the speed within the limits of present knowledge. It is not usual for the determination of the lift and drag of the glider to include the effects of the air-screw owing to the difficulties of reproducing the latter on a small scale. This deficiency is in large part removed by the results of systematic research on the subject, as a result of which it has appeared permissible to eliminate the wings and concentrate on the increase of body resistance, a change which permits of the use of greatly increased models. In the near future it will be possible to carry the experimental work to a greater degree of refinement in the new wind channel of the National Physical Laboratory. The working section of the air-stream is 7 ft. by 14 ft. and will admit the testing of complete models large enough to contain an electric motor for driving the air-screw. This is the only new condition required in the accurate testing of a model aeroplane complete with air-screw.

The outcome of analysis of existing data is the recognition of two effects of the air-screw on the body resistance. The first is a reduction due to the shielding by the boss, and the second and much more important part is an increase which depends on the conditions of working of the air-screw. If R_i' denote the resistance of parts in the slip-stream when the air-screw is working and R_i the value in the absence of air-screw, then it is found that

$$R_i' = R_i\left(0{\cdot}85 + 1{\cdot}2\frac{T}{\rho V^2 D^2}\right) \quad . \quad (27)$$

represents a typical relation between them. T is the thrust of the air-screw, ρ the air density, V the air speed *outside* the slip-stream, and D the diameter of the air-screw. If T be zero, it will be seen that $R_i' = 0{\cdot}85R_i$, the difference between 0·85 and 1·00 being a shielding by the boss which was referred to earlier. It is in part due to such a shielding as would be caused by a stopped air-screw boss, but also in part to the fact that the flow through an air-screw does not cease when T becomes zero. It is probable that the integral effect which leads to $T=0$ is made up of positive elementary thrusts on the outer parts of the air-screw blades and negative thrusts on the inner parts. The effect of the latter is to reduce the air velocity over the body and so add to the more direct shielding.

The type of equation given in (27) has no known exceptions, the variations observed for different air-screws and bodies being covered by changes in the constants 0·85 and 1·2. This applies even for such striking variation as that produced by changing the air-screw from the front of the body to the rear. It would be expected that reduction of air-screw diameter, which involves an increase of slip-stream velocity for a given thrust, would produce marked changes in the factor 1·2, and in general the factors involved in (27) should be regarded as experimentally determined constants.

With the type of equation shown it is possible to represent simply the glider resistance of an aeroplane as affected by the working of an air-screw. The total resistance of an aeroplane R being divided into its two parts R_o and R_i' respectively due to parts outside the slip-stream and those in the slip-stream, it is to be noted that R_o depends markedly on the angle of incidence as it arises largely from the wings, whilst R_i' is not sensibly dependent on angle of incidence over the normal angles of flight. An approximate value for R is then obtained in the form

$$R = R_o + R_i\left\{a + b\left(\frac{V}{nD}\right)^{-2} k_T\right\}, \quad . \quad (28)$$

where k_T is the thrust coefficient defined in equation (9) and R_o, R_i, a and b are experimentally determined quantities. The effect of the air-screw slip-stream on lift is small and is usually neglected, whilst angles of climb are small enough to come within the definition $\cos\theta = 1$ to an order of accuracy sufficient for present needs. The lift equation is then simply

$$L = W, \quad . \quad . \quad . \quad . \quad (29)$$

where W is the weight of the aeroplane.

To the same degree of approximation it is found that

$$T = R + W\frac{V_c}{V}, \quad . \quad . \quad . \quad (30)$$

the equivalent physical idea being that the angle between the line of action of the thrust and the drag axis is small and that the effect on the forces acting is proportional to the cosine of this angle.

Introducing the lift and drag coefficients of (5) into (28-30) leads to an equation

$$\left\{\frac{D^2}{S}-b(k_D)_i\right\}\left(\frac{V}{nD}\right)^{-2}k_T=(k_D)_o + a(k_D)_i+k_L\cdot\frac{V_c}{V}. \quad (31)$$

The valuation of k_T is experimental and depends to a small extent on the presence of the body and wings of the aeroplane. The dependence on angle of incidence is so small that no measurements of it have yet been made. k_T is determined from measurements of the thrust of the air-screw with the body in place (a model is used) and is a function of V/nD. The whole of the left-hand side of (31) then becomes a function of V/nD and may usefully be adopted as an air-screw characteristic and be denoted by K_T. Similarly the two items of drag $(k_D)_o$ and $a(k_D)_i$ may be represented together by a drag coefficient K_D, and with this notation (31) becomes

$$K_T=K_D+k_L\cdot\frac{V_c}{V}. \quad . \quad . \quad (32)$$

The torque of the air-screw with body and wings in place is usually determined at the same time as the thrust, and the necessary condition for engine and air-screw balance is

$$Q_e=Q_a, \quad . \quad . \quad . \quad (33)$$

a relation which is only of importance when the engine is "all out."

The necessary experimental data for use with equations (31-33) are typified by *Fig.* 1 (*a*), (*b*), (*c*), and (*d*).

Equation (33) differs from that given earlier only in the fact that, to a first approximation, Q_e has been shown to be independent of a. If P be defined as $2\pi nQ$, equation (33) can be expanded to show that

$$\left(V\sqrt{\frac{\rho}{w}}\right)^3=\frac{S}{2\pi D^2}\left(\frac{V}{nD}\right)^3\cdot\frac{1}{k_Q}\cdot\frac{P}{W}\sqrt{\frac{\rho}{w}}. \quad (34)$$

For a given state of the atmosphere defined chiefly by ρ, P is a known function of n for the engine when fully out and (34) is seen to lead to a relation between V and n and known quantities represented by *Fig.* (1). The relation between V and n or V/nD is independent of the rate of climb of the aeroplane but not of the height in the atmosphere. In general there is, for an increase of height of 10,000 ft., a small reduction of revolutions at a given true speed of flight.

Once the relation between V and n has been determined in this way equation (34) gives a relation which connects the quantities $V\sqrt{\rho/w}$ and $P/W\sqrt{\rho/w}$.

From equation (32) is obtained a further relation which depends on the angle of incidence of the wings. K_D is a function of angle of incidence, and therefore of k_L, which can be represented as in *Fig.* 1 (*a*). K_T is similarly an experimental result deduced from the curve for k_T in *Fig.* 1 (*b*) and the expression for K_T given in equation (31). To see the connection of (32) with those deduced for generalised variables rewrite as

$$V_c\sqrt{\frac{\rho}{w}}=\frac{K_T-K_D}{k_L}, V\sqrt{\frac{\rho}{w}}, \quad . \quad (35)$$

or since

$$k_L=\left(V\sqrt{\frac{\rho}{w}}\right)^{-2}, \quad . \quad . \quad (36)$$

$$V_c\sqrt{\frac{\rho}{w}}=(K_T-K_D)\left(V\sqrt{\frac{\rho}{w}}\right)^{-1}. \quad (37)$$

The relation shown by (37) depends both on angle of incidence and on V/nD. In level flight V_c is zero and hence $K_T=K_D$. This equation is solved without difficulty by a process of graphical solution of simultaneous equations. It has already been seen that from (34) simultaneous values of V and V/nD can be found if the engine is all out. Using this knowledge, assume a value for V/nD and deduce K_T from the air-screw characteristics; the corresponding value of V leads to k_L from (36) and the value of k_T may then be plotted against the calculated value of k_L. Repetition leads to a curve intersecting that of drag and gives the required solution of (37) which determines the angle of incidence, the speed V, and the advance per revolution V/nD when the thrust balances the drag. For a given state of the atmosphere and the engine "all out" the solution is unique and gives the maximum speed of the aeroplane in level flight.

In climbing flight the solution involves more labour; one of the simpler methods is to give an arbitrary value to k_L and hence to k_D, and to use (37) and the relations between V and n in order to calculate V_c. The maximum rate of climb is then found by plotting a number of values of V_c on a basis of k_L. A trial will show that the precision in the determination of k_L is not great whilst that of V_c is considerable. Physically this means that the rate of climb near the maximum is not greatly dependent on the speed of flight.

§ (9) Analysis of Aeroplane Performance into the Items which depend on Engine, Aeroplane Glider, and Air-screw. — If the data required for prediction are available, it is possible to make comparison with observed results, and agreement would, in general, indicate the substantial accuracy of the separate items of the data. It rarely happens that a designer of an aeroplane finds himself in such a fortunate position, and consequently discrepancies of some importance exist between the expected performance and

that achieved. In investigations which result it is desirable that the analysis of the achieved results should depend as little as possible on facts drawn from comparisons with roughly representative models. It is not, however, possible to dispense with ideas of general applicability, and the theory of analysis is less rigid than that of prediction.

The knowledge which commonly exists as a foundation for analysis includes a test of the engine for power under standard atmospheric conditions. In flight, observations are made of the maximum speed of the aeroplane at various levels up to 20,000 ft. or more, and of the maximum rate of climb at all levels. In special cases supplementary observations are made with the engine throttled and with the angle of descent changed.

From these observations it is desired to deduce as much as possible of the information typically represented by *Fig.* 1 (*a*), (*b*), and (*d*). That is, an effort is to be made to deduce the drag coefficient as a function of lift coefficient, the thrust and torque coefficients of the air-screw, and the variation of engine power with height for the actual atmosphere of the trials. The key to the method to be described comes from a realisation that the air-screw characteristics can be approximately covered by three constants and a set of curves of universal application. The three constants correspond with changes of scale of the abscissae of *Fig.* 1 (*b*) and of the ordinates of the thrust and torque coefficient curves. The standard set of curves is shown in *Fig.* 3 and involves the use of a quantity called experimental mean pitch, denoted by p and defined as the advance per revolution of the air-screw (V/n) when the thrust is zero. Reference to *Fig.* 1 (*b*) will show that in that instance p was equal to 1·14D.

The three constants which are characteristic of an individual air-screw are T_C, Q_C, and p (*Fig.* 3), and these are to be deduced by analysis of performance trials.

If P_S represent the engine power under standard conditions, it is assumed as before that $f(h) . P_S$ will represent the power at some height h, the form of f depending on the distribution of density and temperature in the atmosphere at the time of the trials. $f(h) . P_S$ is the quantity hitherto denoted by P and is the actual power delivered by the engine. By equation (34) it then follows that

$$\frac{k_Q}{f(h)} = \frac{1}{2\pi\rho D^5} \cdot \frac{1}{n^3} \cdot P_S, \quad . \quad (38)^1$$

and hence, since P_S depends only on n, it is possible to deduce values of $k_Q/f(h)$ from the observations of n taken during flight. Since

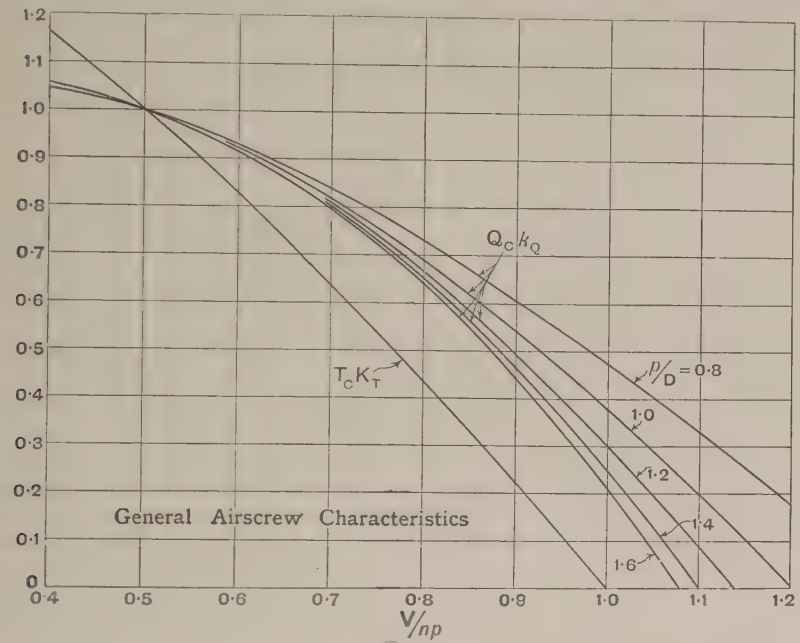


FIG. 3.

[1] A gear ratio of unity for air-screw to engine is assumed for simplicity. The changes in the equations for other values are readily made.

V is also observed it is easy to deduce V/nD, and by the assumption of a value for p to extract a value of $Q_C k_Q$ from the standard air-screw curves. Combining this result with equation (38) leads to an evaluation of a quantity $Q_C/f(h)$ which for a constant height must be independent of the rate of climb. Two values for $Q_C/f(h)$ at a given height are obtained from the maximum speed and the maximum rate of climb, and these values will only be equal for a particular value of the pitch p. This value is easily found by trial and error or by graphical solutions for the condition that $Q_C/f(h)$ is constant so long as the height of trial is unchanged.

In this way the value of p is determined with all the accuracy demanded by the data.

The next step in the analysis is to use this value of p in connection with (38) and the observations of V/nD to deduce values of $Q_C/f(h)$ for experiments with the engine "all out." The observations usually range from the ground to a level near the ceiling of the aeroplane, and check points occur which indicate the correctness of the value assigned to p. Both Q_C and $f(h)$ are readily deduced from the values of $Q_C/f(h)$ by plotting the ratio on an abscissa of height, for where the height is such as to give standard density the value of $f(h)$ is unity, and hence the ordinate at that point is equal to Q_C. In any actual reduction it appears that $f(h)$ is very closely a linear function of density; the effect of temperature is small and cannot be shown except by a further experiment in a different atmosphere. In general it would appear that the temperature should be regarded as introducing corrections which may be determined on a test bench and not from observations in the air.

The values of the experimental mean pitch p, the torque coefficient factor Q_C, and the power factor for height $f(h)$ have followed entirely from a consideration of the air-screw and engine torques. To deal with thrust and drag the aeroplane glider is introduced by means of the lift coefficient k_L. The lift coefficient is here defined as the total force on the aeroplane and air-screw divided by the air density, the area of the wings, and the square of the velocity. The amount contributed by the wings depends on the angle of incidence, and the lift coefficient is not therefore that of the wings. The quantity defined has a considerable precision as a function dependent on angle of incidence only. Equation (36) is then used to deduce k_L from observations in flight. From the quantities previously evaluated and the observations of V/nD it is easy to deduce the value of $T_C K_T$ from the standard curves for air-screws, and the determination of T_C then presents little difficulty.

If we examine (36) and (37) it will be seen that the latter can be written as

$$V_c\sqrt{\frac{\rho}{w}} = (K_T - K_D)\sqrt{k_L}, \quad . \quad (39)$$

and K_D is a function of k_L. From the series of level flights some value of k_L can be found from the velocity which will give

$$\frac{1}{T_C}(T_C K_T)_l - K_D = 0, \quad . \quad . \quad (40)$$

where $(T_C K_T)_l$ is known, as seen above. From the series of observations at maximum climb a second relation is obtained as

$$\frac{1}{\sqrt{k_L}} \cdot V_c\sqrt{\frac{\rho}{w}} = \frac{1}{T_C}(T_C k_T)_C - K_D. \quad (41)$$

Equations (40) and (41) suffice to determine both T_C and K_D. From each pair of values of T_C, K_T, and K_D for a given k_L there will be a separate determination of T_C and K_D, and as the former is an absolute constant the results so obtained must be subjected to some process of weighted means such as that given by the method of least squares. When once this has been effected equation (41) provides the necessary relation between K_D, k_L, and the observations taken in flight.

This is as far as the general analysis can be taken. To make the results directly comparable with those obtained in a wind channel it would be necessary to estimate the values of a and $\{(D^2/S) - b(k_D)i\}$ of equation (31) and apply them to the values of K_D and K_T deduced as above. There is little uncertainty in either estimation and the analysis is then completed.

In considering analysis carried out in this way it appears that in general the accuracy possible is of value in tracing the cause of a discrepancy between prediction and achievement. At the highest speeds reached, however, the lack of rigidity of the air-screw blades may introduce large errors into the evaluation of K_D and K_T. The effect of this twist is, however, readily detected by the fact that the curves for K_D depart markedly from the general form known to exist for aeroplane gliders.

§ (10) The Performance of Airships.—The calculations relating to airships are very different from those for aeroplanes and aerodynamically are much simpler. The dynamic lift is a relatively small item and the equation between thrust and drag is sensibly independent of inclination of the axis of the airship to the direction of motion for all practicable angles. The equations given for the aeroplane, Nos. (11) and (12), apply in the most general case, but (13) is modified to

$$R = W - B, \quad . \quad . \quad . \quad (42)$$

where B is due to the buoyancy of the hydrogen. R is then generally a small quantity, and the usual consideration of performance assumes that it is zero. Since angle of incidence does not appear, the equivalent of (11) and (12) leads to the equation

$$k_D = F\left(\frac{V}{nD}\right), \quad . \quad . \quad . \quad (43)$$

where k_D is the drag coefficient of the envelope, cars, and rigging. Since k_D is a constant, it follows that a single air-screw can only run at one value of V/nD, and the problem of design is therefore greatly simplified as compared with that for an aeroplane where a high efficiency is desired over a range of values of V/nD. In the usual case of more than one air-screw a large number of combinations is possible, but these cannot be covered by any simple rules. The drag coefficient becomes

$$k_D = F_1\left(\frac{V}{nD}\right) + F_2\left(\frac{V}{nD}\right) + \ldots \quad (44)$$

where F_1 depends on the first air-screw, F_2 on the second, and so on.

The determination of k_D presents great difficulties, for the largest model which can be tested in a wind channel is very small compared with the smallest airship, and variations of the coefficient, although not very great at the upper end of the model range, are sufficiently great to render extrapolation somewhat dangerous. In the absence of accurate full-scale measures of resistance our present state of knowledge indicates a rough agreement between the uncorrected coefficients on the model and those for the airships.

There is no possibility of analysing airship performance on the lines adopted for the aeroplane. It will be realised that the accuracy of the determination for the aeroplane depends on the fact that, near the ground, a large part of the available engine power (up to $\frac{2}{3}$) may be used in producing climb and that the dynamometer which comes from a consideration of the rate of lifting the weight of the aeroplane is a good one. The vertical movement of the airship arises from causes totally unconnected with aerodynamics and provides no basis for the foundation of a theory of analysis.

The vertical equilibrium of an airship presents new problems. In essentials, all airships, whether rigid or non-rigid, are supported by the displacement of air by hydrogen, the latter being contained in a flexible bag. In order to maintain the external form of a non-rigid airship, the whole volume is completed by a second flexible bag containing air, and the gases are kept under a small pressure sufficient to give rigidity to the structure. The variations of volume of either set of gas containers are regulated partly automatically and partly by hand. In the rigid airship the external form is maintained by a metal and fabric structure, and the flexible hydrogen containers float inside this structure.

Owing to the similarity of the laws of expansion of gases it follows that a given mass of hydrogen will displace a given mass of air, no matter what the pressure may be, so long as the temperature of the two is the same. If, therefore, perfect flexibility of container be presumed, an airship will not have its equilibrium permanently disturbed by change of height in the atmosphere. There will, however, be some state of expansion for which the hydrogen holders will completely fill the internal space of the airship, and when once that point is reached additional height can only be attained by discharge of ballast. If a height of 20,000 ft. is to be reached without loss of ballast, the flexible gas-bags must not be more than half full at ground level.

Although the permanent state of equilibrium is not changed, it is clear that some time must elapse before the temperature of the gas inside the container is equal to that outside, unless the connection between pressure and temperature in the latter is that required for adiabatic expansion. In that case instantaneous equilibrium would be attained at all heights. If the air temperature increases more rapidly than is required by the adiabatic law, an airship, if raised accidentally, would tend to return to its first level, and the state may be described as stable. The standard atmosphere is one which gives appreciable temporary stability, and it is obvious, by replacing the hydrogen by air, that the conditions for airship stability for height are those which lead to absence of convection currents in the atmosphere.

In the case of a temperature inversion the argument developed above would indicate some difficulty in the handling of an airship.

L. B.

AIRCRAFT, THE STABILITY OF — ITS THEORETICAL AND EXPERIMENTAL DETERMINATION

§ (1) Introduction. — The consideration of the motion of aircraft introduces problems of varying degrees of complexity; in many cases the statement of the hypothesis involves many variables, each containing a simple idea but leading to considerable complications when taken together. To this class belongs the problem of the stability of the motion of aircraft as generally understood at the present time. The theory — at any rate for aeroplanes — was given form and connection with the older theory of rigid dynamics by Professor G. H.

Bryan,[1] who adopted the formulae for dealing with the small oscillations of a rigid body about a state of steady motion from the standard works of Routh and others. In order to apply the formulae in the case of aviation it is first necessary to know a great deal about the forces acting on the aircraft due to motion through the air. As the information cannot be obtained from a theory of aerodynamics based on a knowledge of the shape of a body, the nature of the motion, the physical properties of the air and the equations of fluid motion, it is necessary at the outset to resort to experimental work. The results of observation are expressed in a series of functions of angle of incidence, and for complete motion in three dimensions the number of members of the series is thirty-six. In rectilinear motion half of the series suffices, and this half again divides into two groups, one relating to longitudinal stability and the other to lateral stability. In the longitudinal motion are involved the velocity of flight, the rise and fall of the aircraft and its pitching; laterally, appear the velocity of side-slipping combined with rolling and yawing. Bryan showed [1] that in rectilinear motion the two groups are mathematically separable on the assumptions made. As a matter of exact application, it would appear that gyroscopic action of the air-screw and certain effects of the slip-stream on the tail of an aircraft modify this conclusion so as to remove the rigid mathematical proof. There is little apparent effect on the practical truth of the theorem of separation.

§ (2) Definitions of the more important Terms used in the Theory of Stability.[2] (i.) *Axes.*—*Longitudinal Axis.*—A straight line in the plane of symmetry of an aircraft through the centre of gravity, fore and aft. In general theoretical discussions of the motion of an aeroplane this may be taken as parallel to the air-screw axis. The positive direction is taken forwards from the centre of gravity. In mathematical theory this axis is taken as the "X" axis.

Lateral Axis.—A straight line through the centre of gravity normal to the plane of symmetry of an aircraft. In an aeroplane the lateral axis is conveniently taken parallel to a line joining the wing-tips, and when looking in the direction of motion of the aircraft the positive branch of the axis is to the right. In mathematical theory this axis is taken as the "Y" axis.

Normal Axis.—A straight line in the plane of symmetry, at right angles to the longitudinal axis and through the centre of gravity. Where the longitudinal and lateral axes are horizontal, the normal axis is vertical. The positive direction is downwards in all aircraft. In mathematical theory this axis is taken as the "Z" axis.

The axes are fixed in the aircraft and move with it.

(ii.) *Velocities.*—*Longitudinal Velocity.*—The component velocity of an aircraft in the direction of its longitudinal axis, relative to the air. Symbol "u."

Lateral Velocity or Rate of Side-slipping.—The component velocity of an aircraft in the direction of its lateral axis, relative to the air. Symbol "v."

Normal Velocity.—The component velocity of an aircraft in the direction of its normal axis, relative to the air. Symbol "w."

Rolling.—Angular motion about the longitudinal axis. Symbol "p."

Pitching.—Angular motion about the lateral axis. Symbol "q."

Yawing.—Angular motion about the normal axis. Symbol "r."

(iii.) *Angles.*—*Angle of Bank.*—The angle through which the aircraft must be turned about the longitudinal axis, whether horizontal or inclined, to bring the lateral axis to a horizontal position. As a common case in horizontal normal flight, the angle of bank is the inclination to the horizontal of the line joining the wing tips of an aeroplane. Symbol "ϕ."

(iv.) *Stalling.*—An aeroplane is said to be stalled when the speed is so reduced that it ceases to be under control. This occurs when the angle of incidence is in excess of the critical angle.

(v.) *Controls.*—The controls of an aeroplane are arranged as follows:

(*a*) Pulling the control column back has the effect of raising the elevators and leads to an increase in the angle of attack of the wings.

(*b*) Moving the control column to the left has the effect of raising the left aileron and ultimately causing a depression of the left wing. The same motion lowers the right aileron and the total effect is a large rolling moment. There is a secondary yawing moment produced simultaneously.

(*c*) Movement of the rudder bar by the right foot puts the rudder over to the right and ultimately produces a turn to the right.

§ (3) Air Forces acting.—Bryan made the hypothesis that the forces on heavier-than-air craft depended only on the linear and angular velocities of the relative motion and mathematically expressed the components of air force and air moment in the form

$$X = f_X(u, v, w, p, q, r), \quad . \qquad (1)$$

[1] *Stability in Aviation*, Bryan.

[2] The nomenclature and symbols used in the mathematical theory of the stability of aircraft have been standardised by the Royal Aeronautical Society in *A Glossary of Aeronautical Terms*, and the definitions above are extracted from that source.

where X may be longitudinal force for illustration, u, v, w the linear velocities of the centre of gravity of the aircraft along its co-ordinate axes, and p, q, r the angular velocities of these axes relative to the air. For convenience of calculation the axes of reference are fixed in the aircraft and rotate with it, whilst certain other advantages follow if the axes of reference are also the principal axes of inertia of the aircraft.

The hypothesis represented by (1) is well supported by experiment and is still adopted. Bryan hesitated to apply the same assumption to airships on account of the large inertia of the air displaced by the envelope which, it was anticipated on theoretical grounds, would modify the forces as a result of accelerations. For lighter-than-air craft, therefore, the corresponding expression to (1), so far as it is known, is

$$X_1 = f_X'(u, v, w, p, q, r, \dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}), \quad (2)$$

and this statement of the requirements from the experimental side will show how difficult the complete problem may rapidly become by the addition of terms dependent on simple general hypotheses.

Before stability can be examined it is necessary to satisfy the equations of steady motion. From this part of the problem are determined certain related values of u, v, and w . . ., which may be denoted by u_0, v_0, etc. Variations from these values are then supposed to exist as the result of gusts, movement of controls, or any other cause, but to be so small that an expansion of X in the form

$$X = f_X(u_0, v_0, w_0, p_0, q_0, r_0) + \delta u \frac{\partial f_X}{\partial u} + \delta v \frac{\partial f_X}{\partial v} + \ldots + \delta p \frac{\partial f_X}{\partial p} + \ldots \quad (3)$$

is sufficient if first powers of δu, δv, etc., be retained. The quantities $\partial f_X/\partial u$, $\partial f_X/\partial v$ . . . are referred to as resistance derivatives and are the experimental functions referred to earlier. For ease of manipulation it is common to use u instead of δu and to write X_u for $\partial f_X/\partial u$.

§ (4) Resistance Derivatives.—Although $\partial f_X/\partial u$ is a function of u_0, v_0, etc., it does not depend on the values of δu, δv, etc., within the limitations of the expansion given in (3). It is therefore possible to determine its value experimentally by a simple experiment in which a small increase of velocity is given to the air. All the derivatives with velocity suffixes are determinable by standard methods of testing such as are used in obtaining data for the steady motion or performance.

Derivatives due to angular velocities are less easily found; in many cases they represent forces and couples which damp the motion, and a convenient means of estimation then arises from observation of the rate of damping of an oscillation of a model aircraft in an artificial wind. In other cases the couple is forcing, viz. a yawing of an aeroplane changes the velocity of the wings so as to produce a rolling couple, and the difficulties of devising a suitable experiment for its determination have only recently been overcome. It has then happened that experimental data have been supplemented by a certain amount of calculation, the basis of which is indicated by the following illustration.

Suppose that the tail of an aeroplane is narrow and so far behind the centre of gravity that all parts are sensibly at a distance l from it. Owing to a small angular pitching velocity q of the aeroplane the tail will have a linear velocity lq relative to the centre of gravity. If the motion of the aeroplane be along the tail with velocity U_0, it will be seen that the resultant effect is an inclination of the relative wind at the tail of lq/U_0 radians. The limitation placed on lq is that it shall be small as compared with U_0. If the aerodynamic properties of the tail are known, the above illustration shows how the forces on the tail-plane due to the oscillation may be based on observation of a non-oscillating but inclined tail-plane. A wide application of this principle is made and has already led to important results in explaining observed phenomena.

In the case of lighter-than-air craft further experiments are required in which the motion is accelerating. It is known from general hydrodynamics that the resistance of the air moved by an accelerating sphere can be represented as equal to the force necessary to give the acceleration of the sphere to a mass of air equal to half that displaced by the sphere. The cylinder accounts for a larger relative amount, and it appears that in the case of the broadside motion of an airship the apparent mass moved is nearly twice the mass of the airship itself. This is a very important amount and some few experiments have been made to determine it. In order to make the inertia effect as great as possible air has been displaced by water. To the towing carriage of the tank used for testing model ships was attached a model airship wholly submerged and capable of an oscillation across the direction of motion. The period of oscillation was observed and found to be very much greater than the period *in vacuo* (or air), and from the difference it is easy to calculate the effect of lateral acceleration which shows itself as a virtual addition to the mass of the moving body.

The determination of the derivatives required by the theory of stability fixes the rate of progress possible in developing the subject and requires the provision of a considerable amount of apparatus and skilled observers. Very much work is yet required before the possibility of generalisation exists; on the other hand, results have already been obtained which show the sufficiency of the hypotheses to account for the main disturbed motions of aircraft as observed in free flight.

§ (5) Standard Axes.—In order to facilitate cross reference between various workers in

Stability a certain number of ideas and symbols have been recommended by the Royal Aeronautical Society and accepted by prominent official bodies interested in aeronautics. One of the more important items defines axes of reference for aircraft of all descriptions. The origin, as already stated in § (2), is situated at the centre of gravity [1] of the aircraft with the axis of Z pointing vertically downwards in steady horizontal flight, the axis of X directed forward and facing in the direction of motion, and the axis of Y to the right. This definition, although only an approximate one, gives a clear idea of the general arrangement of the axes; since these move with the aircraft the exact position depends on the conditions of the flight, and in a mathematical investigation precision is given to position of axis in the statement of the problem. If the principal axes of inertia are chosen there will be no difficulty in maintaining the general idea of position as indicated above.

§ (6) Equations of Motion.—Relative to the system of axes so defined the equations of motion of a rigid body are found in treatises on Rigid Dynamics, and are: [2]

$$\left.\begin{aligned} \dot{u}+wq-vr&=X' \\ \dot{v}+ur-wp&=Y' \\ \dot{w}+vp-uq&=Z' \\ \dot{p}A-rq(B-C)&=L' \\ \dot{q}B-pr(C-A)&=M' \\ \dot{r}C-qp(A-B)&=N \end{aligned}\right\} \quad . \quad . \quad . \quad (4)$$

Principal axes of inertia have been chosen for simplicity, and the moments of inertia about the axes of X, Y, and Z are denoted by A, B, and C. The forces and moments $mX' \ldots N'$ depend partly on motion through the air as defined by the velocities and angular velocities $u, v, \ldots q, r$ and their derivatives, and partly on the components of the weight of the aircraft.

In certain detailed problems departures of some importance are made from the ideas connected with rigid bodies. The control surfaces, consisting of elevator, rudder, and aileron, are held to the aeroplane through the pilot's limbs, and the assumption of rigidity is then probably valid. In particular experiments, however, it is customary to abandon the elevator and ailerons and to leave them relatively free to rotate about their hinges. In this case new equations of motion are required which are usually defined to ensure that the moments about the hinges are zero. A somewhat less satisfactory assumption is made to cover the connection between the air-screw and aeroplane glider which amounts to the neglect of the inertia of the air-screw and the rotating parts of the engine. The assumption is convenient since it is substantially correct for the slower motions of an aeroplane which give rise to the problems of great practical importance. It is, however, not sufficiently accurate in a discussion of the rapid motions of an aeroplane where the times of importance are limited to less than one or two seconds. Both instances of lack of rigidity may be regarded as modifications of the general theory of secondary importance, and the further work is based on equations (4) as given.

In general, the pilot has considerable powers to change four of the quantities $X', \ldots N'$, though in no case is the effect of the movement of a control confined to one of the quantities concerned. The effect of an increase in engine power due to opening of the throttle has its first result in a change of thrust and therefore of X'; due to the fact that the elevator and rudder are both washed by the air-screw slip-stream; there are also changes of M' and N' which may be of great importance on the resulting motion. Apart from these complications, the effect of an increase in thrust is an increase of the inclination of the flight-path to the horizontal and not an increase in flying speed.

A change in the position of the elevator produces a couple M' with little other effect. The result is, first, a change in attitude which leads to a new speed of flight, and, secondly, an alteration of the inclination of the flight path to the horizontal so as to provide an adjustment of power to maintain this new speed.

Movement of the ailerons alone produces a large rolling couple L' and a smaller yawing couple, whilst the rudder produces a couple N' and as a result of turning a rolling couple which tends to raise the faster-moving outer wing. For certain relative adjustments of ailerons and rudder it is possible to turn without side-slipping.

It will be seen that four controls are provided, whilst six conditions of equilibrium are to be satisfied, as shown by (4). It follows that the aeroplane must be so constructed as to deal with the other two. Three of the controls enable the pilot to put the craft into any angular position desired relative to the wind, whilst the engine allows some control over one of the forces. The angular movements suffice to ensure that $Y=0$ or has some value depending on side-slipping which is produced by the non-symmetrical presentation to the relative wind. The effect of gravity is to so change the speed of flight and angle of path that the resultant force in steady flight is vertical and equal to the weight of the aeroplane. If the aircraft be stable the adjustments required do not call for an effort from the pilot, but if it be unstable a constant nursing of the craft is involved if it be desired to maintain a particular state of steady motion. In the latter case lack of attention for a period of one minute may result in loss of control either temporarily or permanently,

[1] See "Aircraft, Explanation of Terms."

[2] It is usual to work with forces per unit mass rather than forces themselves.

and it appears that an aeroplane which is unstable in its attitude for normal flight tends to become locked on its back so far as longitudinal control is involved. One type of instability leads to an increasingly steep dive, at the end of which the forces on the control column are greater than the pilot can exert or the column withstand. The importance of stability in reducing the risk of accident is very great, and has perhaps the preponderating influence amongst those things which occur in the air. The other very serious cause of accident is the failure of the engine and is indirect, since the consequences depend on the nature of the available landing grounds.

It is not intended to discuss the problems connected with steady motion at greater length, but it must be clearly borne in mind that the treatment of stability presumes that such a state exists and that the derivatives required are those appropriate to the particular steady motion which is being discussed. From the conditions of steady motion are then deduced those parts of X′ . . . N′ which depend on movement through the air. There remains the consideration of the effects of gravitational attraction. Owing to the fact that the resultant gravitational force passes through the centre of gravity there are no component couples about the axes of reference in the case of the aeroplane. For the airship couples due to gravity and buoyancy combined are introduced.

§ (7) Gravity Force Components. (i.) *The Inclination of the Axes to the Vertical.*—It is necessary to define in some way the inclination of the axes to the vertical and various alternatives may be used. Euler's angular co-ordinates, θ, ϕ, ψ, have been used, but an equally convenient arrangement is given by the direction cosines of the downwardly directed vertical with respect to the body axes of the aircraft. These are denoted by n_1, n_2, and n_3, so that the components of X′, Y′, Z′ due to weight are

$$n_1 g,\ n_2 g, \text{ and } n_3 g \quad . \quad . \quad . \quad (5)$$

along the axes of X, Y, and Z respectively. In the airship there is a vertical upward force due to buoyancy which leads to components of X′, Y′, and Z′ equal to

$$-\frac{n_1 \mathrm{F}}{m},\ -\frac{n_2 \mathrm{F}}{m},\ -\frac{n_3 \mathrm{F}}{m}, \quad . \quad . \quad (6)$$

where m is the mass of the aircraft and F is the buoyancy.

Denoting the co-ordinates of the centre of buoyancy relative to the standard axes by x, y, and z, the component couples are

$$\mathrm{L}=(n_2 z - n_3 y)\mathrm{F},\ \mathrm{M}=(n_3 x - n_1 z)\mathrm{F},$$
$$\mathrm{N}=(n_1 y - n_2 x)\mathrm{F}. \quad (7)$$

It will generally happen that "y" is zero.

(ii.) *Relation between the Angular Velocities of the Steady Motion.*—In order that motion may be steady it must follow that the altitude of the aircraft relative to the air must be unchanged and also the position relative to the vertical. This latter condition can only be satisfied if the resultant rotation is about the vertical, and as a consequence

$$p_0=n_1\Omega,\quad q_0=n_2\Omega,\quad r_0=n_3\Omega, \quad . \quad (8)$$

where Ω is the resultant angular velocity.

§ (8) Disturbed Motion.—The method of procedure is that general in the consideration of dynamical stability. A body in a state of steady motion is supposed to receive some disturbance, which may be simple or complex, but which in the latter case can be reduced to a number of simple disturbances by assuming that the changes of motion are small as compared with the original. In illustration of the idea involved consider the equation

$$\dot{u}+wq-vr=\mathrm{X}', \quad . \quad . \quad . \quad (9)$$

which is one of the members of equation (4), and apply it to the disturbed motion of an aeroplane.

In the steady motion $\dot{u}$ will be zero, whilst w, q, v, r, and X′ will be distinguished by the use of the suffix zero. The introduction of the value for X′, which can be built up from components already determined, shows that (9) becomes

$$\dot{u}+wq-vr=f_{\mathrm{X}}(u,\ v,\ w,\ p,\ q,\ r)+n_1 g. \quad (10)$$

Using the Taylor expansion equation (10) leads to

$$\begin{aligned}\delta\dot{u}+(w_0+\delta w)(q_0+\delta q)-(v_0+\delta v)(r_0+\delta r)&\\ =f_{\mathrm{X}}(u_0,\ v_0,\ w_0,\ p_0,\ q_0,\ r_0)+n_1 g&\\ +\delta u\frac{\partial f_{\mathrm{X}}}{\partial u}+\delta v\cdot\frac{\partial f_{\mathrm{X}}}{\partial v}+\delta w\frac{\delta f_{\mathrm{X}}}{\partial w}+\delta p\frac{\partial f_{\mathrm{X}}}{\partial p}&\\ +\delta q\frac{\partial f_{\mathrm{X}}}{\partial q}+\delta r\frac{\partial f_{\mathrm{X}}}{\partial r}+\delta n_1 g+\text{etc.}, \quad (11)&\end{aligned}$$

and all terms other than those specifically written down are ignored in the theory of small oscillations, together with such products as $\delta w\,.\,\delta q$. Equation (11) is then reduced to

$$\left.\begin{matrix}w_0q_0-v_0r_0\\ +\delta\dot{u}+q_0\delta w\\ +w_0\delta q-v_0\delta r\\ -r_0\delta v\end{matrix}\right\}=f_{\mathrm{X}}(u_0,\ v_0,\ w_0,\ p_0,\ q_0,\ r_0)+n_1 g$$
$$+\delta u\frac{\partial f_{\mathrm{X}}}{\partial u}+\delta v\frac{\partial f_{\mathrm{X}}}{\partial v}+\delta w\frac{\partial f_{\mathrm{X}}}{\partial w}$$
$$+\delta p\frac{\partial f_{\mathrm{X}}}{\partial p}+\delta q\frac{\partial f_{\mathrm{X}}}{\partial q}+\delta r\frac{\partial f_{\mathrm{X}}}{\partial r}$$
$$+\delta n_1\,.\,g, \quad . \quad . \quad (12)$$

and is dealt with in two parts. The equation

$$w_0q_0-v_0r_0=f_{\mathrm{X}}(u_0,\ v_0,\ w_0,\ p_0,\ q_0,\ r_0)+n_1 g \quad (13)$$

states one relation which must be satisfied initially and which will be recognised as a condition of steady motion; equation (13) and the five others deduced from equations (4) define the value of $u_0 \ldots r_0$ for the particular steady motion which corresponds with the assumed positions of the controls and must be solved prior to the discussion of stability.

In rewriting the remainder of equation (12), the more regular notation will be adopted by which δu becomes u and $\delta f_X/\partial u$ becomes X_u. The danger of using the same symbol u for two different ideas should be noticed, as also the fact that little practice is required in order to avoid error. With this note the second part of (12) leads to

$$\dot{u} + q_0 w + w_0 q - v_0 r - r_0 v = uX_u + vX_v + wX_w + pX_p + qX_q + rX_r + \delta n_1 . g. \quad (14)$$

This is one of the six equations of disturbed motion which ultimately lead to the estimation of $u, w \ldots r$ in terms of the derivatives $X_u \ldots$, $Y_w \ldots$. If any of the quantities $u_1 \ldots r$ tend to increase with time the steady motion, defined by equation (13) and its companions, is unstable. Routh has shown how a number of equations of type (14) may be combined into a single equation which determines stability or otherwise, and how the criterion may be applied with the greatest ease. It is also shown in treatises on advanced Rigid Dynamics that the remaining five relations determine the ratios of the magnitudes of $u, v \ldots r$ so that ultimately it is possible to deduce completely the periods and damping factors of oscillatory motion, the rate of subsidence of aperiodic motions, and the details of the motion which result from any initial disturbance. Since the theory of small oscillations permits of the addition of a number of separate disturbances, it is further possible to find the resultant effect of a number of them even though distributed over successive periods of time. The flight of a stable aeroplane in a natural wind is included in the latter case, together with the effect of the manipulation of the controls by the pilot.

It is found, by comparison of theory and experiment, that the theory of small oscillations gives results which are applicable with satisfactory accuracy to the finite oscillations of aircraft. A description of some observations is given later in the article.

§ (9) Evaluation of δn_1.—Equation (11) introduces the expression δn_1 for the variation of the direction cosine n_1 which results from the changes $\delta q \ldots \delta p$, etc., or, in the later notation, $q \ldots p \ldots r$. It is necessary to develop the relation before any solution of (14) is feasible.

Three auxiliary angles α, β, and γ are used in the process and represent displacements of the axes of reference OX, OY, and OZ from their original position. It will be remembered that the downward vertical had direction cosines n_1, n_2, and n_3 relative to the body axes before disturbance. After rotation with angular velocities p, q, and r to the new position the direction cosines of the vertical will be $n_1 + dn_1$, $n_2 + dn_2$, and $n_3 + dn_3$. From *Fig.* 1 it may be deduced that the relations

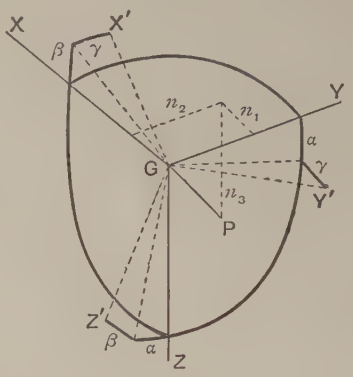


Fig. 1.

between these direction cosines and α, β, γ are

$$n_1 + \delta n_1 = n_1 - n_3\beta + n_2\gamma \quad . \quad . \quad (15)$$

and two similar expressions for n_2 and n_3.

The resultant angular velocity of the axes is made up of the steady motion components p_0, q_0, and r_0, and the disturbances $\dot{\alpha}$, $\dot{\beta}$, and $\dot{\gamma}$, in such a way that

$$\left.\begin{aligned} p &= \dot{\alpha} - r_0\beta + q_0\gamma \\ q &= r_0\alpha + \dot{\beta} - p_0\gamma \\ r &= -q_0\alpha + p_0\beta + \dot{\gamma} \end{aligned}\right\} . \quad . \quad . \quad (16)$$

All solutions of linear differential equations with constant coefficients, such as equation (14), are obtained from a knowledge that

$$\dot{\alpha} = \lambda\alpha, \quad \beta = \lambda\beta, \quad \dot{\gamma} = \lambda\gamma, \quad . \quad . \quad (17)$$

where λ is independent of α, β, and γ. Equations (16) are thereby converted into expressions for α, β, γ in terms of p, q, r as follows:

$$\frac{\alpha}{\begin{vmatrix} -r_0 & q_0 & p \\ \lambda & -p_0 & q \\ p_0 & \lambda & r \end{vmatrix}} = \frac{-\beta}{\begin{vmatrix} \lambda & q_0 & p \\ r_0 & -p_0 & q \\ -q_0 & \lambda & r \end{vmatrix}} = \frac{\gamma}{\begin{vmatrix} \lambda & -r_0 & p \\ r_0 & \lambda & q \\ -q_0 & p_0 & r \end{vmatrix}} = \frac{1}{\begin{vmatrix} \lambda & -r_0 & q_0 \\ r_0 & \lambda & -p_0 \\ -q_0 & p_0 & \lambda \end{vmatrix}} \quad (18)$$

Denoting by Ω^2 the value of $p_0^2 + q_0^2 + r_0^2$, the last expression is found to be

$$\frac{1}{\lambda(\Omega^2 + \lambda^2)}, \quad . \quad . \quad . \quad (19)$$

and from (18) and (15) is deduced the relation

$$dn_1 = \frac{1}{\Omega^2 + \lambda^2}\{(1 - n_1^2)\Omega p - (n_1 q_0 + n_3\lambda)q - (n_1 r_0 - n_2\lambda)r\}. \quad (20)$$

Similar relations follow for dn_2 and dn_3. It is convenient to write μ for $g/(\Omega^2+\lambda^2)$ in the equations of disturbed motion.

§ (10) SEPARATE TREATMENT OF AEROPLANE AND AIRSHIP STABILITIES.—So far the subject has had little reference to the type of aircraft under consideration, and there is no fundamental difficulty in continuing with complete generality. The expressions become so cumbrous, however, and the motions of aeroplanes and airships are so different that it is advisable to consider the problems separately. The mathematical method follows parallel lines in the two cases, and such theorems as that relating to the independence of the longitudinal and lateral disturbances in rectilinear symmetrical motion are common to both types of aircraft.

§ (11) AEROPLANE: *Disturbances in Three Dimensions.*—Treating each of the six equations in (4) as in the case illustrated of the first of them, we obtain the final equations:

$$\left.\begin{array}{lll}
u(\mathrm{X}_u-\lambda) & +v(\mathrm{X}_v+r_0) & +w(\mathrm{X}_w-q_0) \\
+p\{\mathrm{X}_p+\mu\Omega(1-n_1^2)\} & +q\{\mathrm{X}_q-w_0-\mu(n_1q_0+\lambda n_3)\} & +r\{\mathrm{X}_r+v_0-\mu(n_1r_0-\lambda n_2)\} = 0 \\
u(\mathrm{Y}_u-r_0) & +v(\mathrm{Y}_v-\lambda) & +w(\mathrm{Y}_w+p_0) \\
+p\{\mathrm{Y}_p+w_0-\mu(n_2p_0-\lambda n_3)\} & +q\{\mathrm{Y}_q+\mu\Omega(1-n_2^2)\} & +r\{\mathrm{Y}_r-u_0-\mu(n_2r_0+\lambda n_1)\} = 0 \\
u(\mathrm{Z}_u+q_0) & +v(\mathrm{Z}_v-p_0) & +w(\mathrm{Z}_w-\lambda) \\
+p\{\mathrm{Z}_p-v_0-\mu(n_3p_0+\lambda n_2)\} & +q\{\mathrm{Z}_q+u_0-\mu(n_3q_0-\lambda n_1)\} & +r\{\mathrm{Z}_r+\mu\Omega(1-n_3^2)\} = 0 \\
u\,.\,\mathrm{L}_u/\mathrm{A} & +v\mathrm{L}_v/\mathrm{A} & +w\mathrm{L}_w/\mathrm{A} \\
+p(\mathrm{L}_p/\mathrm{A}-\lambda) & +q(\mathrm{L}_q/\mathrm{A}+r_0\overline{\mathrm{B}-\mathrm{C}}/\mathrm{A}) & +r(\mathrm{L}_r/\mathrm{A}+q_0\overline{\mathrm{B}-\mathrm{C}}/\mathrm{A}) = 0 \\
u\,.\,\mathrm{M}_u/\mathrm{B} & +v\mathrm{M}_v/\mathrm{B} & +w\mathrm{M}_w/\mathrm{B} \\
+p(\mathrm{M}_p/\mathrm{B}+q_0\overline{\mathrm{C}-\mathrm{A}}/\mathrm{B}) & +q(\mathrm{M}_q/\mathrm{B}-\lambda) & +r(\mathrm{M}_r/\mathrm{B}+p_0\overline{\mathrm{C}-\mathrm{A}}/\mathrm{B}) = 0 \\
u\,.\,\mathrm{N}_u/\mathrm{C} & +v\mathrm{N}_v/\mathrm{C} & +w\mathrm{N}_w/\mathrm{C} \\
+p(\mathrm{N}_p/\mathrm{C}+q_0\overline{\mathrm{A}-\mathrm{B}}/\mathrm{C}) & +q(\mathrm{N}_q/\mathrm{C}+p_0\overline{\mathrm{A}-\mathrm{B}}/\mathrm{C}) & +r(\mathrm{N}_r/\mathrm{C}-\lambda) = 0
\end{array}\right\} \quad (21)$$

Equations (21) give relations between known quantities, u_0, v_0 . . ., p_0 . . ., X_u . . ., Y_u . . ., L_u, n_1, n_2, n_3, A, B, and C, and λ, v/u, w/u, p/u, q/u and r/u, and the last five are determinable by the ordinary methods for the solution of linear simultaneous equations. The evaluation of λ constitutes the special condition connected with stability. λ may be real, in which case a negative value indicates stability and a positive value instability, the motion being aperiodic. If λ be complex the motion indicated is an oscillation, and stability is then indicated by a negative sign for the real part of the root. In general there are eight roots of the equation for λ, consisting of three complex pairs and two real roots; the equation itself is derived by the elimination of five of the variables u, v . . . r from equation (21), and, in accordance with methods of solution of algebraic equations, is frequently left as a six-row determinant the value of which is to be zero by choice of λ.

§ (12) AEROPLANE. (i.) *Rectilinear Symmetrical Flight.*—It was pointed out by Bryan [1] that many of the derivatives can be seen from considerations of symmetry alone to be zero in steady rectilinear symmetrical flight. For instance, $v\mathrm{X}_v$ represents the change of longitudinal force per unit mass due to sideslipping; from the symmetry of the aeroplane and its motion it is clear that $v\mathrm{X}_v$ cannot change sign with v, and hence X_v must be zero. It then appears that

X, Z, and M with suffixes v, p, and r (22)

are zero under the assumed conditions, as are also

Y, L, and N with suffixes u, w, and q. (23)

Since the steady motion is rectilinear

p_0, q_0, and r_0 are zero, . . (24)

whilst symmetry requires that

n_2 and v_0 are zero and $\mu=\dfrac{g}{\lambda^2}$, since $\Omega^2=0$. (25)

Making use of these relations converts equations (21) to

$$\left.\begin{array}{llll}
u(\mathrm{X}_u-\lambda) & +w\mathrm{X}_w & +q\left(\mathrm{X}_q-w_0-\dfrac{n_3g}{\lambda}\right) & = 0 \\
v(\mathrm{Y}_v-\lambda) & +p\left(\mathrm{Y}_p+w_0+\dfrac{n_3g}{\lambda}\right) & +r\left(\mathrm{Y}_r-u_0-\dfrac{n_1g}{\lambda}\right) & = 0 \\
u\mathrm{Z}_u & +w(\mathrm{Z}_w-\lambda) & +q\left(\mathrm{Z}_q+u_0+\dfrac{n_1g}{\lambda}\right) & = 0 \\
v\mathrm{L}_v/\mathrm{A} & +p(\mathrm{L}/\mathrm{A}-\lambda) & +r\mathrm{L}_r/\mathrm{A} & = 0 \\
u\mathrm{M}_u/\mathrm{B} & +w\mathrm{M}_w/\mathrm{B} & +q(\mathrm{M}_q/\mathrm{B}-\lambda) & = 0 \\
v\mathrm{N}_v/\mathrm{C} & +p\,.\,\mathrm{N}_p/\mathrm{C} & +r(\mathrm{N}_r/\mathrm{C}-\lambda) & = 0
\end{array}\right\} \quad (26)$$

and it will be found that the first, third, and fifth equations involve the variables u, w, and q,

[1] *Stability in Aviation.*

and not v, p, and r, whilst the second, fourth, and sixth depend on v, p, and r only. Bryan pointed out that this indicates independence of the longitudinal and lateral disturbances.

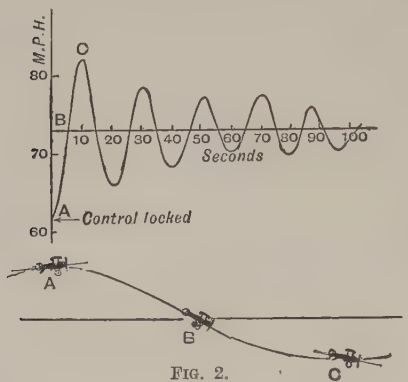


FIG. 2.

The longitudinal disturbances involve fore and aft motion, up and down motion and pitching, and are described as symmetrical as being all in the plane of symmetry. The lateral group, consisting of side-slipping, rolling, and yawing, are correspondingly designated "asymmetrical."

Each group leads to a biquadratic equation for λ, and the numerical evaluation of the roots presents little difficulty.

(ii.) *Remarks on the Roots of the Equations for Longitudinal Stability.* — The derivatives and constants of the stability equations (26) apply to one particular state of steady motion. In general the quantities vary markedly with the velocity of flight, particularly so in the neighbourhood of the least possible velocity of steady flight. An aeroplane may be stable for some speeds of flight and not for others, and a tendency towards instability often accompanies an increase of speed. The disturbed longitudinal motion is usually divisible into two parts, the first being very rapid and confined to one or two seconds after disturbance, and the second quite slow and often periodic in a time of 20 to 30 secs. The rapid movements are those which bring the aeroplane into approximate equilibrium of conditions relative to the air, and the slow movements those which bring the aeroplane back to its initial position relative to gravity.

Observations of oscillations are easily recorded during the flight of an aeroplane. A pin-hole camera is fixed to the aeroplane and directed over the tail whilst the aeroplane is flown directly away from the sun. The pilot starts a definite pitching movement, and the trace of the sun on a moving photographic film leads to an important record of stability. An equivalent record (see *Fig.* 2) is that of the forward speed of the aeroplane. The rapid movements having been damped out a remainder is left from which the period and damping factor of importance can be deduced. In the illustration the period was about 20 secs. and each maximum less than its predecessor in the proportion of about 3 to 4. Such record is an adequate guarantee of stability with the control locked; a similar record could have been taken with the control abandoned. There is no important difference in the character of the records in the two cases.

The first sign of instability in an aeroplane which has this characteristic oscillation usually appears as a lengthening of the period of oscillation, ultimately to an infinite value. Mathematically this corresponds with a reduction of the imaginary part of a complex root to zero and the replacement of a pair of complex roots by two real roots, one of which is positive. The final effect, physically, is illustrated by *Fig.* 3, which shows a record deduced from direct experiment: with

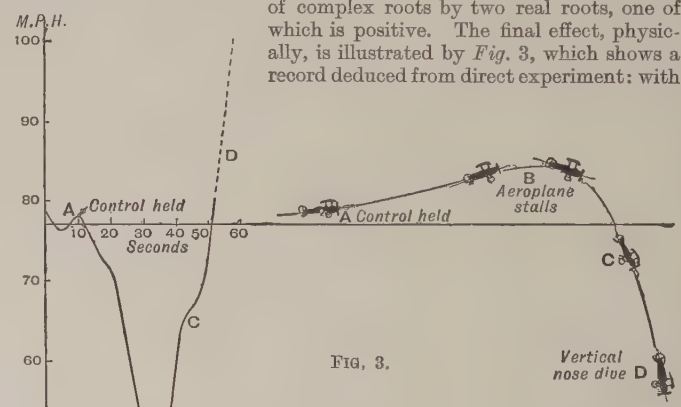


FIG. 3.

the controls held the aeroplane gradually lost speed until support was not possible (aeroplane stalled), then put its nose down and tended to a vertical or over-the-vertical dive.

This type of instability is dangerous; it can be shown that control becomes extremely sensitive when the motion first becomes aperiodic, and that for instability the final movements of the control column are in the opposite direction to those for stability. As the aeroplane gathers speed the forces on the control column grow rapidly; if the aeroplane be stable the pilot needs to push in order to

increase the rate of diving, and when the forces get too great the aerodynamics of the problem set a limit to the steepness of the dive. In the case of instability the aeroplane tends to dive more steeply whilst the pilot is pulling on the column. If recovery is delayed too long the force involved is so great that the pilot is unable to control the motion, and in some instances he is thrown from his seat whilst the aeroplane flies upside-down. It appears to be a somewhat general rule that an aeroplane which is longitudinally unstable in normal flight will be stable in inverted flight,

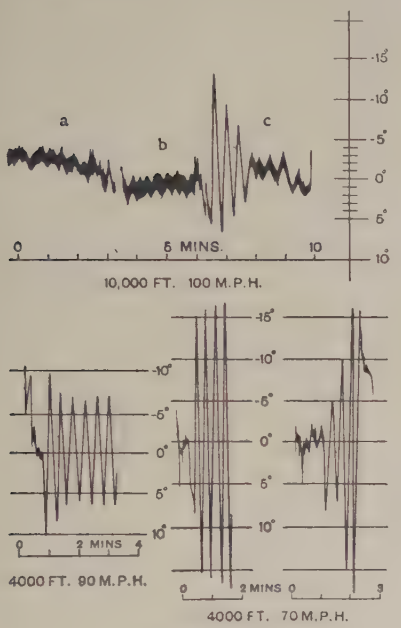


FIG. 4.

and *vice versa*. Recovery from stable inverted flight comes from the lateral motions.

Instability which shows itself at low speeds takes the form of an oscillation of increasing amplitude, but is rarely observed. *Fig.* 4 shows one of the few records available on this point. At 100 m.p.h. the record marked (*a*) was obtained with the pilot in control, whilst for (*b*) the aeroplane was allowed to control itself with the column abandoned. A comparison indicates a considerable degree of effectiveness of the inherent stability. The large regular oscillation was produced by the pilot, who put the aeroplane into a dive and then abandoned control. A period of 20 to 25 seconds is indicated with marked damping of the oscillations. At 90 m.p.h. the period is little changed, but the damping becomes very small after the first two periods. A further reduction of speed shows an increasing oscillation, the increase of amplitude in the second figure being in part due to the fact that the aeroplane was climbing slightly in the steady motion. The motion is slow and easily dealt with by the pilot, and cannot be classed as dangerous although it is undesirable. In the mathematical investigation this type of instability is indicated by a change in sign of the real part of the complex pair of roots.

The exact conditions to be satisfied in order to ensure stability depend on an accurate balance of two large quantities, represented on one side by the restoring couple due to the tail and on the other by the movement of centre of pressure of the wings. The former is appreciably dependent on the downwash of air from the main planes and by the slip-stream of the air-screw. It appears to be possible to make a good first approximation to the desired result and by a correction after flight tests to bring an aeroplane to a specified state of longitudinal stability. The amount specified does not yet rest on any clear basis for fighting craft, but is known roughly for bombing aeroplanes and civilian craft, where steady flight for long periods is aided materially by stability.

(iii.) *Remarks on the Roots of the Equation for Lateral Stability.*—The character of the lateral motion is very different from that of longitudinal motion, but again depends primarily on the speed of the steady motion. At the lowest speeds of steady flight remarkable changes occur, which will be dealt with separately. Excluding these changes, it is found that over the normal range of steady flight, the roots are partly real and partly complex. Of the real roots one represents a rapidly damped subsidence which becomes unimportant in a fraction of a second as compared with its initial value. The characteristics are readily worked out and show that the motion is almost wholly that of a roll about the longitudinal axis, and the damping arises from the increase of lift on the downward-moving wing and a decrease on the opposite wing. The aeroplane is left with one wing down and recovery occurs through the lateral oscillation and a slower subsidence, both of which are affected by a dihedral angle between the wings. The lateral oscillation appears to have the relatively short period of 5 or 6 seconds and is generally well damped. It is possible but very unusual to experience a lateral oscillation of increasing amplitude.

The remaining component of a lateral disturbance is a slow spiral motion which may decrease or increase for a time. Its origin is clear on physical grounds. Imagine the aeroplane to be travelling in a straight line initially, but with the right wing down. Side-slipping will begin to the right and a side wind will be produced which, acting on the

rudder, will turn the aeroplane to the right. The left wing will then be turning in a circle of larger radius than the right and hence at a higher velocity, the result being an increase of lift under the left wing as compared with the right. This tends to increase the banking and further depress the right wing. A compensating couple comes into being as a result of side-slipping if the wings have a lateral dihedral angle, since the latter has the effect of relatively increasing the angle of incidence and therefore lift on the right wing. When this latter couple is great the aeroplane recovers an even level and is stable; when it is small the overbanking preponderates and the result is a spiral. In general the motion is slow and easily controlled, and the need for rapid manœuvring in warfare has provided a strong reason for large rudder rather than spiral stability.

At low speeds lateral instability becomes marked and often dangerous. If, whilst in steady horizontal flight, the control column is pulled steadily back until stalling occurs the sequence of events is usually the following: immediately after stalling the aeroplane drops its nose rapidly and at the same time one wing goes down. A little later the body may be inclined to the horizontal at an angle of 70 to 80 degrees and be rotating about a vertical at a small radius. The rate of descent is not nearly so great as in a dive and rarely exceeds half the terminal velocity. The state is permanent, and it needs a definite effort on the pilot's part to resume normal flight. The method adopted for recovery involves essentially the restoration of a higher speed of flight and is attained by putting the column forward. The state of spin then becomes unstable and that of rectilinear flight stable; the spin stops rapidly and a normal dive takes its place.

The phenomenon is well known in flying circles and its essential features can be reproduced in a simple experiment. A model of an aeroplane wing may be mounted in an artificial wind so as to be free to rotate about an axis parallel to the wind direction. If the angle of incidence be small, *i.e.* corresponds with a high speed of free flight of an aeroplane, the wing oscillates in accordance with the fluctuations in the wind. For a large angle of incidence, such as is taken by a stalled aeroplane, the wing takes up a continuous rotation which is measurable and, to a high degree of accuracy, calculable. Some of the more insistent modern problems arise from a study of this rotation, and an improvement of control at low speeds may be anticipated as a result of a realisation of its causes.

Owing to the difficulty of the measurements there are no records of lateral movements at the moment which compare directly with *Figs.* 2, 3, and 4. Not only are the motions more complex in type, but the pilot has two controls, the ailerons and rudder, and rarely abandons the latter. The most common type of motion therefore is one in which the direction of the craft is maintained by human control. Under these circumstances stability is easily attained. It is doubtful whether the more complete stability indicated by fixing of all controls is given by the normal construction of the present period (1923).

(iv.) *Curvilinear Flight.*—It has already been remarked that curvilinear steady flight can only occur when the resultant rotation is about a vertical axis. The possibilities include circling in a horizontal plane, with or without the correct banking to avoid side-slipping and a spiral ascent or descent. Vigorous side-slipping tends to produce difficulties with lateral control and to initiate a spinning nose-dive and is generally avoided by pilots. The full theoretical analysis is lengthy and is limited by the experimental data available, on the one hand, and by the difficulty of extracting the points of generality from the particular results to which resort must be made in order to obtain solutions at all.

If attention be confined to symmetrical curvilinear flight, *i.e.* flight without side-slipping, it would appear that the aerodynamic derivatives may be deduced with sufficient accuracy from those in rectilinear motion. The terms of equation (21) which indicate interaction between the longitudinal and lateral disturbances arise as the result of centrifugal components of force. The combined effect of a uniform acceleration and gravitational attraction is indistinguishable from that of a new gravitational field of increased strength and of changed direction, and it is found in particular instances that the differences between the stability of curvilinear and rectilinear flight are appreciable for those parts which depend on gravity. Since the aerodynamic derivatives are not changed in any important particular for the flight assumed, it is not surprising to find that the disturbed curvilinear motions which arise in the adjustment of the aeroplane to the condition of zero air-moments are not materially different from those arising in rectilinear flight.

It is necessary to bear in mind certain restrictions as to conditions of comparison. Resistance derivatives are complex functions of angle of incidence, but, if that be kept constant, vary as the speed of motion and as the air density for a given mass of aeroplane. In order to fly at a given angle of incidence on a banked turn the speed of flight must be greater than that for rectilinear flight at the same angle of incidence. It then follows that the derivatives are greater for a particular aircraft in circular flight than is the case for

straight flight, and as a consequence the disturbed motions are more rapid and more heavily damped.

For the rapid parts of the disturbances, therefore, the period of oscillation is decreased in proportion to the square root of the velocity, whilst the damping factor is increased in proportion to the velocity, and these are the only sensible changes. The same general law accounts for such changes as occur in the lateral oscillation, which falls between the two extremes, of aerodynamic motions which are fast and independent of gravity and those which are slow and are called into operation as a result of gravitational attraction. In the last group falls the longitudinal oscillation with a period of 20 to 30 secs., and the spiral subsidence of divergence of the lateral motion; between the two there is a considerable degree of interaction. An aeroplane which is laterally unstable in straight flight tends to become stable as the result of turning, whilst the longitudinal stability is reduced. It is quite possible for the conditions of stability to be reversed within the limits of flight of a powerful craft.

The above deductions are based on flight at an angle of incidence well removed from the critical value, and it is not to be expected that they will apply even approximately to the motions which precede a spin.

The labour involved in a full investigation of stability by the known methods is sufficient to preclude much general analysis. It is to be hoped that the designers of the future will, in the interests of safety and comfort, make a detailed estimate of the properties of their own craft.

§ (13) Airship.—The treatment of airship stability differs from that of the aeroplane in two important particulars. In the first place the deviations from the conditions of rectilinear flight which are possible are not so great as to modify vitally the nature of the disturbed motion, and it is sufficient to consider the longitudinal and lateral motion as separable under all circumstances. This is true even in the special case of the motion of an airship with its axis slightly inclined to the direction of motion, although the result is remarkable in showing that a great access of stability is obtained by an airship which follows a sinuous path, first turning in one direction and then in the other, as compared with the same airship in strictly rectilinear flight for its steady motion. The explanation of the difference appears from a consideration of the aerodynamics relating to the moments on the airship. With the fins directly in the wake of the airship the shielding by the envelope is very large, whereas a moderate angle of yaw (2 or 3 degrees) may suffice to increase the restoring moment some two or three times.

The second cause of difference between the applied theory of stability for airships and aeroplanes arises from the buoyancy terms and the accelerations of the air due to the large bulk of the envelope. If the airship be in static equilibrium, the buoyancy force F exactly balances the weight of the craft and no components appear in the force equations as a result of inclinations of the aircraft. The centre of buoyancy is, however, some distance above the centre of gravity, and inclinations relative to the vertical lead to component couples. The direction cosines n_1, n_2, and n_3 then appear as important expressions only in the equations for L, M, and N.

Some note has already been taken of the effects of fluid acceleration in developing equation (2), which states the precise assumptions made at the present time in dealing with the problems of the motion of lighter-than-air craft.

(i.) *Steady Motion.*—An airship is provided with two main controls, elevator and rudder. At rest, the control of trim can be effected by a suitable distribution of the weights carried, but the moments so produced are small compared with the aerodynamic moments which can be applied by the elevators at moderate speeds of flight. No lateral control exists to correspond with the wing flaps of an aeroplane, and the pilot has therefore no independent control of the banking of the ship. The stability against rolling which comes from the action of buoyancy and weight is very great and large angles of bank do not occur. This stability is not materially affected by motion through the air.

(ii.) *Stability Equations.*—If rectilinear motion and symmetry about a vertical plane through the axis of the airship be presupposed the stability equations become

$$\left.\begin{aligned}
\dot{u}+w_0q &= -\frac{n_3}{\lambda}\left(g-\frac{\mathrm{F}}{m}\right)q + u\mathrm{X}_u + w\mathrm{X}_w + q\mathrm{X}_q \\
&\quad + \dot{u}\mathrm{X}_{\dot{u}} + \dot{w}\mathrm{X}_{\dot{w}} + \dot{q}\mathrm{X}_{\dot{q}} \\
\dot{w}-u_0q &= \frac{n_1}{\lambda}\left(g-\frac{\mathrm{F}}{m}\right)q + u\mathrm{Z}_u + w\mathrm{Z}_w + q\mathrm{Z}_q \\
&\quad + \dot{u}\mathrm{Z}_{\dot{u}} + \dot{w}\mathrm{Z}_{\dot{w}} + \dot{q}\mathrm{Z}_{\dot{q}} \\
\dot{q}\mathrm{B} &= (n_1x+n_3z)\mathrm{F}\frac{q}{\lambda} + u\mathrm{M}_u + w\mathrm{M}_w + q\mathrm{M}_q \\
&\quad + \dot{u}\mathrm{M}_{\dot{u}} + \dot{w}\mathrm{M}_{\dot{w}} + \dot{q}\mathrm{M}_{\dot{q}}
\end{aligned}\right\} \quad (27)$$

$$\left.\begin{aligned}
\dot{v}+u_0r &= \left(\frac{n_2p}{\lambda}-\frac{n_1r}{\lambda}\right)\left(g-\frac{\mathrm{F}}{m}\right) + v\mathrm{Y}_v + p\mathrm{Y}_p + r\mathrm{Y}_r \\
&\quad + \dot{v}\mathrm{Y}_{\dot{v}} + \dot{p}\mathrm{Y}_{\dot{p}} + \dot{r}\mathrm{Y}_{\dot{r}} \\
\dot{p}\mathrm{A} &= \left(\frac{n_2p}{\lambda}-\frac{n_1r}{\lambda}\right)\mathrm{F}z + v\mathrm{L}_v + p\mathrm{L}_p + r\mathrm{L}_r \\
&\quad + \dot{v}\mathrm{L}_{\dot{v}} + p\mathrm{L}_{\dot{p}} + r\mathrm{L}_{\dot{r}} \\
\dot{r}\mathrm{C} &= -\left(\frac{n_2p}{\lambda}-\frac{n_1r}{\lambda}\right)\mathrm{F}x + v\mathrm{N}_v + p\mathrm{N}_p + r\mathrm{N}_r \\
&\quad + \dot{v}\mathrm{N}_{\dot{v}} + p\mathrm{N}_{\dot{p}} + \dot{r}\mathrm{N}_{\dot{r}}
\end{aligned}\right\} \quad (28)$$

The difference between the weight, mg, and the lift, F, due to displacement of air by hydrogen must be small, in which case the balance can be provided by dynamic lift from the envelope, which arises when motion occurs through the air with the axis inclined to the direction of motion. The co-ordinates x and z are those of the centre of buoyancy relative to the standard axes through the centre of gravity. Of the derivatives required for accelerations only a few have yet been evaluated. $X_{\dot{u}}$ and $Z_{\dot{w}}$, $Y_{\dot{v}}$, $N_{\dot{r}}$, $M_{\dot{q}}$ are known to be important, and a few values are available for use.

The two series of stability equations are deduced from (27) and (28) by eliminating any two of the three variables u, w, and q for (27), or v, p, and r for (28). The result in each case is to produce a biquadratic equation for λ, the solution of which determines the character of the stability. The equations can further be used to determine the ratios w/u, q/u, p/v, and r/v for the disturbed motion, and hence the full details if required.

(ii.) *Approximate Criteria for Airship Stability.* — From a very general consideration of the magnitude of the quantities involved it is possible to deduce approximate formulae of practical utility. It is found that a first root of (27) is nearly equal to

$$\lambda=\frac{X_u}{1-X_{\dot{u}}}, \quad . \quad . \quad . \quad (29)$$

and the physical interpretation is that the disturbances of forward motion are damped out aperiodically, with little effect on the up and down motion or on the pitching. The term X_u is essentially negative, as is also $X_{\dot{u}}$. The latter may be regarded as an addition to the virtual mass of the airship, its value being estimated by its relation to unity. A not improbable value for $X_{\dot{u}}$ is $-0{\cdot}25$. After eliminating the root given by (29) from the full equation derived from (27) there is left a factor with the approximate value

$$\begin{vmatrix} Z_w-\lambda(1-Z_{\dot{w}}) & u_0+Z_q \\ M_w & M_q-(B-M_{\dot{q}})+Fz/\lambda \end{vmatrix}, \quad (30)$$

which is a cubic in λ. Using the theory of equations and a knowledge of the signs of the terms involved, it may be shown that the cubic represents an oscillation and a subsidence. The only possible instability then arises from an increase in the amplitude of the oscillation, and the condition for real damping is easily found to be

$$\begin{vmatrix} M_q & u_0+Z_q \\ M_w & Z_w-\dfrac{Fz(1-Z_{\dot{w}})^2/B}{M_q(1-Z_{\dot{w}})/B-M_{\dot{q}}+Z} \end{vmatrix}>0, \quad (31)$$

whilst the periodic time of the oscillation at the moment instability shows itself is

$$T=2\pi\sqrt{-\frac{B}{Fz}\left\{1+\frac{M_q(1-Z_{\dot{w}})}{B-M_qZ_w}\right\}}. \quad . \quad (32)$$

A less exact criterion for longitudinal stability is given by

$$\begin{vmatrix} M_q & u_0+Z_q \\ M_w & Z_w \end{vmatrix}=0, \quad . \quad . \quad (33)^1$$

which is derived from the condition that no critical velocity exists. Aerodynamically it means that the fins are so large that a restoring moment is produced without the assistance of gravity and buoyancy. Engineering limitations in the fixing of fins to airship envelopes restrict the possibilities, and it is therefore preferable to use (31) and to ensure that the critical speed of the craft exceeds the possible speed of flight. Owing to the expansion of the gas containers the value of the buoyancy-gravity couple will decrease with height, and the critical velocity will therefore be lower on this account. The air forces are also reduced in proportion to the density and this has a tendency in the reverse direction.

The existence of a critical velocity may always be suspected when part of the restoring couple depends on gravity and is therefore invariable with speed, whilst the couples due to fluid reaction increase as the square of the speed.

The solution of the lateral stability equation obtained from (27) leads to a different type of result. It has been remarked that the stability against rolling which is provided by the gravity-buoyancy couple is large, even at the highest speeds of flight, and therefore involves the presence of a stable oscillation. The approximate factor which is deduced from (27) and a consideration of the values of the derivatives involved is

$$\lambda^2+zL_v/A-zF/A=0. \quad . \quad . \quad (34)$$

The middle term is introduced by the motion and gives a measure of the damping. Unless very great, the effect of this term on the period of roll will be very slight. The last term gives the quantity from which the period is mainly determined and does not depend on the motion of the airship.

The only type of lateral instability which appears to be possible is that corresponding with a real positive root of the stability equation, and to ensure stability it is necessary that

$$\begin{vmatrix} Y_v & -u_0+Y_r \\ N_v & N_r \end{vmatrix}>0. \quad . \quad . \quad (35)$$

[1] With $Z_q=0$ this condition was given by Crocco in 1907.

It is noteworthy that this condition does not depend on any of the derivatives which arise from the consideration of the acceleration of the air by the motion of the airship. The term N_v depends on the yawing moment about a vertical axis through the centre of gravity of the airship. A careful examination of (35) shows that an airship in free flight may be stable, whereas the same ship regarded as a weathercock on an axis through the centre of gravity would be unstable and tend to turn its tail into the wind.

§ (14) Stability of other Types of Aircraft.—A certain amount of work exists on the stability of kites and kite balloons. The new points arise from the constraint of the kite wire, and various assumptions are made as to the effect of its weight and air resistance. It is probable that the wave transmission is almost as important as any of the secondary effects where the tension is great. The changes are those of detail, and the theory proceeds on the general lines adopted for aeroplanes and airships. Until a sufficient number of derivatives have been experimentally determined to admit an estimate of their importance little progress will be possible in the direction of effective approximate formulae. It appears that the ratio of the periodic time of the oscillation of a body about its point of attachment to a wire and that of the end of the wire is of great importance in determining the character of the motion of a tethered body such as a kite balloon.

§ (15) Effect on an Aeroplane of Small Movements of Controls and Encounters with Gusts.—In order to proceed to the problems now indicated it is necessary to depart from the strict consideration of stability. The previous analysis is still necessary in order to obtain the values of λ which determine stability, but more is required. An example of the type of problem contemplated can be given by supposing an aeroplane in steady longitudinal flight to be disturbed by the pilot pushing his control column forward slightly. The final effect is an increase of speed on a downward path if the aeroplane be stable; the process by which the aeroplane passes from its initial to its final state of motion is that which will now be examined. The analysis will be confined to rectilinear motion, as this covers the theory completely and illustrates the more important practical deductions. Solutions of the equations of disturbed motion as given in (26) have the form

$$u=ae^{\lambda t},\ w=be^{\lambda t},\ q=ce^{\lambda t}. \quad . \quad (36)$$

for the longitudinal motion, with similar expressions for v, p, and r in the lateral disturbances. Choosing the group of longitudinal equations for immediate consideration, it will be seen that they become

$$\left.\begin{aligned} &X_u-\lambda+X_w\frac{b}{a} &&+(X_q-w_0-gn_3/\lambda)\frac{c}{a}=0\\ &Z_u &&+(Z_w-\lambda)\frac{b}{a}+(Z_q+u_0+gn_1/\lambda)\frac{c}{a}=0\\ &M_u &&+M_w\frac{b}{a}+(M_q-B\lambda)\frac{c}{a}=0 \end{aligned}\right\}, \quad (37)$$

i.e. three equations for the determination of λ, b/a, c/a. The first of these has been dealt with in the earlier part of this article, and any two of the equations (37) may then be used to find b/a and c/a. The solution is readily obtained, in general terms, both when λ is real and when complex. In the latter case it is necessary to consider a pair of roots and to evaluate the real and complex parts separately. There being four roots for λ, the solution takes the form

$$\left.\begin{aligned} u&=Ae^{\lambda_1 t}+Be^{\lambda_2 t}+Ce^{\lambda_3 t}+De^{\lambda_4 t}\\ w&=A'e^{\lambda_1 t}+B'e^{\lambda_2 t}+C'e^{\lambda_3 t}+D'e^{\lambda_4 t}\\ q&=A''e^{\lambda_1 t}+B''e^{\lambda_2 t}+C''e^{\lambda_3 t}+D''e^{\lambda_4 t} \end{aligned}\right\}, \quad (38)^1$$

where the ratios A′/A, A″/A, etc., are given by the solution of the first two equations of (37).[1] The quantities A, B, C, and D are arbitrary until the initial disturbance is specified. If at a time which may be taken as zero the aeroplane in steady motion encounters a horizontal gust of magnitude u_1, it follows that

$$\left.\begin{aligned} u_1&=A+B+C+D\\ 0&=A'+B'+C'+D'\\ 0&=A''+B''+C''+D''\\ 0&=\frac{1}{\lambda_1}A''+\frac{1}{\lambda_2}B''+\frac{1}{\lambda_3}C''+\frac{1}{\lambda_4}D'' \end{aligned}\right\}, \quad (39)$$

where the fourth equation is obtained from the condition that $\int q dt$ is zero. The relations between A′ and A, etc., are such that all the equations are linear in A, B, C, and D and are readily solved. A typical result is shown in *Fig.* 5. In general, the coefficients of (38)

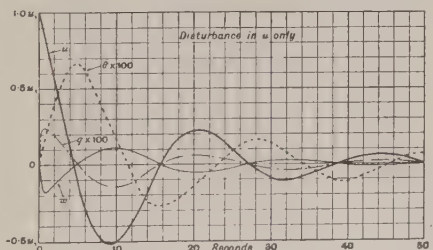


Fig. 5.

[1] Confusion between the two meanings for B in (37) and (38) is easily avoided and the duplication of the use of symbols is necessary in some form or other.

are functions of the nature of the initial disturbance.

If the disturbance is due to the pilot's movement of the elevator or the engine throttle, it is necessary to determine from the proportions of the aeroplane what are the constants which define the initial disturbance. The following method is convenient: the movements of the controls being small, the magnitude of the effect produced is taken to be proportional to the movement of the control, and the constant of proportionality is of a similar nature to the derivatives already used. Using μ for the elevator movement, the quantity itself may refer to the angular motion of the elevator about its hinge or the linear motion of some point on the control column. The change in X due to a movement μ is denoted by the expression μX_μ, whilst a similar expression defines the change of thrust per unit mass due to a movement of the throttle lever as νX_ν.

The equation of motion along the axis of X now becomes

$$0 = n_1 g + f_X(u_0, w_0, 0) - n_3 g\frac{q}{\lambda} + uX_u + wX_w + \mu X_\mu + \nu X_\nu,$$

where n_1, f_X, and n_3 refer to the initial steady motion, and hence the first pair of terms is separately zero. From this and its two companion equations are then deduced the equations for the initial disturbances in u, w, and q/λ which follow from changes in μ and ν. They are

$$\left.\begin{aligned} -n_3 g\frac{q}{\lambda} + uX_u + wX_w + \mu X_\mu + \nu X_\nu &= 0 \\ n_1 g\frac{q}{\lambda} + u\,Z_u + w\,Z_w + \mu\,Z_\mu + \nu Z_\nu &= 0 \\ uM_u + wM_w + \mu M_\mu + \nu M_\nu &= 0 \end{aligned}\right\}. \quad (40)$$

There is, of course, no change in q, since this must be zero in any rectilinear steady motion. q/λ represents a change in the inclination of the axis of X, as will be seen from the equation

$$\lambda\theta = \dot{\theta} = q.$$

Regarding μ and ν as arbitrarily disposable constants, it will be seen that equations (40) are sufficient to determine quantities u, w, and q/λ, which represent initial disturbances. They are of course the differences between the respective quantities in the initial and final steady motions. *Fig.* 6 shows in a particular instance how an aeroplane moves from one state of steady motion to another when the elevator is moved suddenly.

The effect of changing the position of the engine-throttle lever is very closely analogous to that produced by altering the inclination of the fore and aft axis of the aeroplane, and oscillations of large amplitude are set up. After the expiration of less than two seconds the residual disturbance is always of the same character, no matter what the initial disturbing cause. The curves follow in the

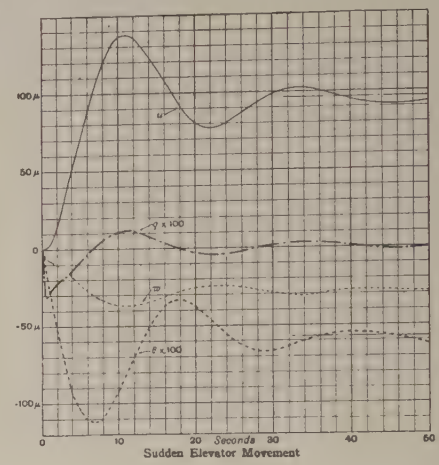


FIG. 6.

same relative position and the same relative proportions for amplitudes of the oscillations in u, w, q, and θ. Variations of forward speed of the relative wind and inclination of the fore and aft axis to the horizontal are taken up slowly by the aeroplane, whilst vertical components in the wind or rotations about a horizontal axis across the line of flight are transferred to the aeroplane with great rapidity.

The treatment of lateral disturbances follows very closely the lines indicated above. The prominent motion is the lateral oscillation with a period of a few seconds. A rapid rolling subsidence produces a banked condition, and side-slipping and yawing follow. At the end of ten to twenty seconds a laterally stable aeroplane would have recovered from any disturbance. If spirally unstable, it would then be in a state little different from the steady motion, except in the case of banking; but all the residual motions begin to increase in magnitude, and when large cease to be covered by the theory of small oscillations. As was pointed out in connection with the theory of the stability of curvilinear motion, the instability tends to disappear as the result of turning. The gusts to be investigated in lateral disturbances are those which produce side-slipping, turning, and rolling. The controls are the rudder and wing-flaps, and it is not difficult to deduce the proportionate movements which are required to ensure that turning shall occur without side-slipping.

The calculations of the disturbed motion

when the disturbing causes all operate at zero time presents little difficulty, and when once the experimental quantities have been deduced is a rapid process. In concluding this section an outline will be given of a general method of treatment when the disturbing causes continue to operate. An instance in point is the flight of an aeroplane in a natural wind. In this case the theory is not strictly applicable, since the fluctuations of velocity of the relative wind are finite and the method is only applicable on strict mathematical grounds to indefinitely small variations. Used with discretion, the results may be applied to real problems with great advantage.

(i.) *Continuous Disturbing Causes.*—It is a fundamental property of the small oscillations of an aeroplane that they co-exist without reference to each other. Not only may a number of disturbances of a simple type be superposed at a given instant, but to the residual disturbances at some subsequent time may be added new complex changes. For ease of explanation the cause will be primarily assumed to be a continuous movement of the elevator initiated by the pilot such that

$$\mu = \mathrm{F}(t). \quad . \quad . \quad . \quad . \quad (41)$$

At a time τ the instantaneous sudden movement may be taken as

$$d\mu = \mathrm{F}'(\tau)d\tau, \quad . \quad . \quad . \quad . \quad (42)$$

and it has been seen in equations (39) and (40) how to deduce the resulting motion, illustrated in *Fig.* 6 for an isolated sudden elevator movement. For this case the constants A, B, C, and D of equation (38) are known from the properties of the aeroplane. The quantity t there used denoted the lapse of time from the disturbance and must now be reconsidered. If t be now defined as the lapse of time from some stated zero, and τ be the time from this same zero to the disturbance $d\mu$, there will be an elementary addition to the velocity u of

$$du = \{\mathrm{A}e^{\lambda_1(t-\tau)} + \mathrm{B}e^{\lambda_2(t-\tau)} + \mathrm{C}e^{\lambda_3(t-\tau)} + \mathrm{D}e^{\lambda_4(t-\tau)}\}\mathrm{F}'(\tau)\delta\tau \quad (43)$$

for all times t subsequent to τ. The cumulative effect of all disturbances up to time t will then be

$$u = \int_0^t \{\mathrm{A}e^{\lambda_1(t-\tau)} + \mathrm{B}e^{\lambda_2(t-\tau)} + \mathrm{C}e^{\lambda_3(t-\tau)} + \mathrm{D}e^{\lambda_4(t-\tau)}\}\mathrm{F}'(\tau)d\tau. \quad (44)$$

Equation (44) is of very general application; it was developed on the hypothesis that $\mathrm{F}(t)$ represented a movement of the elevator and that the constants A, B, C, and D are those appropriate to a sudden isolated elevator movement and the effect on the velocity u of the aircraft was found. Instead of the elevator, a change of engine throttle position could be used with corresponding changes in the constants A-D. Further, an examination of the variations of w, q, and θ due to changes in the controls follows the type equation. Finally, $\mathrm{F}(t)$ may represent gusts of any description such as those which occur in a natural wind.

The form of $\mathrm{F}(t)$ may be very complicated and not suitable for analytical expression; this is particularly the case when it represents the fluctuations of velocity in a natural wind. Since equation (44) involves the first differential coefficient, its form is therefore not that most suitable for calculation. By means of a partial integration equation (44) becomes

$$u = (\mathrm{A}+\mathrm{B}+\mathrm{C}+\mathrm{D})\mathrm{F}(t) - (\mathrm{A}e^{\lambda_1 t} + \mathrm{B}e^{\lambda_2 t} + \mathrm{C}e^{\lambda_3 t} + \mathrm{D}e^{\lambda_4 t})\mathrm{F}(0) - \int_0^t \{\lambda_1 \mathrm{A}e^{\lambda_1(t-\tau)} + \lambda_2 \mathrm{B}e^{\lambda_2(t-\tau)} + \lambda_3 \mathrm{C}e^{\lambda_3(t-\tau)} + \lambda_4 \mathrm{D}e^{\lambda_4(t-\tau)}\}\mathrm{F}(\tau)d\tau. \quad (45)$$

The first term on the right-hand side represents a disturbance in u proportional to the disturbing cause $\mathrm{F}(t)$; the second term arises from an isolated change at $t=0$ of magnitude $\mathrm{F}(0)$, and the initial conditions may generally be chosen to satisfy the condition $\mathrm{F}(0)=0$. The third term may be evaluated graphically without special effort. If the disturbing cause is a gust, it will be found that $\mathrm{A}+\mathrm{B}+\mathrm{C}+\mathrm{D}=1$, and in the case of a horizontal natural wind the whole of the first term is the wind velocity over the ground. The integral of (45) then represents the velocity of the aeroplane over the ground.

A precaution is necessary in proceeding to an example. A little thought will show that the disturbances met with by an aeroplane in flight will not be those registered by an anemometer fixed to an observatory, from which alone records are obtainable. A not improbable assumption is made that the gusts in the air represent fluctuations or eddies which are superposed on an average uniform flow. From this it follows that the time of the record may be reduced in proportion to the ratio of the velocity of the aeroplane to the average wind velocity and then assumed to apply to the former. In other words, the assumption is made that the same gusts are encountered in passing a given distance through air no matter what the velocity of transit. For the general purposes of the theory of stability the assumption is amply justified.

The number of calculations made on the basis of (45) is not great, but there is little doubt that a high-speed aeroplane (upwards of 100 miles per hour) can be made sufficiently stable to control itself longitudinally in winds short of a gale. It is not equally certain that the conditions would be those most conducive to comfort, for recovery takes place by a process of switchbacking. When the ideas involved come to be applied in practice there is some reason to believe that an additional device will be used in order to produce an aeroplane which is both stable and comfortable. How far this can be achieved is unknown, but it is evident from existing analysis that some of the responses of the aeroplane to gusts are so rapid as to be sensibly uncontrollable.

(ii.) *Continuous Control.*—In steady straight flight it may be taken for granted that the controls are used in such a way as to minimise the effect of gusts in disturbing the aeroplane. At the time of alighting, vertical velocity is avoided, while under other circumstances it may be desirable to reduce the pitching of the craft. Mathematically this indicates that the u of (45) is predetermined and that it is required to find $\mathrm{F}(t)$ from the equation. The value of u may first be taken as due to a simple isolated disturbance and a value of the elevator movement found which produces a neutralising effect. The method of summation for a succession of gusts is

then readily expressed in the same form as before where the control was not used.

The vertical velocity of an aeroplane due to an isolated horizontal gust at time $t=0$ has been shown to have the form

$$\dot{h}_{\text{gust}} \equiv (u \sin\theta - w\cos\theta)_{\text{gust}} = A_3 e^{\lambda_1 t} + B_3 e^{\lambda_2 t} + C_3 e^{\lambda_3 t} + D_3 e^{\lambda_4 t}. \quad (46)$$

If, before the elevator is put over, the aeroplane be flying steadily, the equation derived from (44) by partial integration leads to an expression

$$\dot{h}_{\substack{\text{continuous}\\ \text{elevator}}} = -\int_0 \{A_2 e^{\lambda_1(t-\tau)} + B_2 e^{\lambda_2(t-\tau)} + C_2 e^{\lambda_3(t-\tau)} + D_2 e^{\lambda_4(t-\tau)}\} F(\tau) d\tau. \quad (47)$$

The values $A_2 \ldots D_3$ differ from those of $\lambda_1 A$, $\lambda_2 B$, etc., of (45) because the former refer to vertical velocity and the latter to horizontal velocity. Equating (46) and (47) with a view to making the elevator disturbance eliminate the effect of the gust yields the equation

$$A_3 e^{\lambda_1 t} + B_3 e^{\lambda_2 t} + C_3 e^{\lambda_3 t} + D_3 e^{\lambda_4 t} = \int_0 \{A_2 e^{\lambda_1(t-\tau)} + B_2 e^{\lambda_2(t-\tau)} + C_2 e^{\lambda_3(t-\tau)} + D_2 e^{\lambda_4(t-\tau)}\} F(\tau) d\tau, \quad . \quad . \quad . \quad . \quad (48)$$

from which to find $F(t)$. It has been pointed out by Sir J. J. Thomson that an analytical solution of (48) is given by

$$F(t) = A_1 e^{K_1 t} + B_1 e^{K_2 t} + C_1 e^{K_3 t} + D_1, \quad . \quad (49)$$

and that the values of K_1, K_2, and K_3 are found by a solution of the cubic equation

$$0 = \frac{A_2}{K-\lambda_1} + \frac{B_2}{K-\lambda_2} + \frac{C_2}{K-\lambda_3} + \frac{D_2}{K-\lambda_4}, \quad (50)$$

with other equations for A_1, B_1, C_1, and D_1. There are only a limited number of disturbances to which (49) can be applied, for on physical grounds it will be clear that the effects of a sudden isolated horizontal gust on the speed of the aeroplane through the air cannot be countered by anything short of an infinite airscrew thrust. This of course indicates a very artificial initial assumption, but should be borne in mind in any application.

If the control is to be satisfactory the elevator must ultimately return to its initial position, and in (49) it must happen that $D_1=0$ and that K_1, K_2, and K_3 are negative.

A less rigorous solution of (48) allows for a partial elimination of a disturbance; instead of exact correction at all times, it may be presumed that a short interval of time elapses during which the full amount of control is applied without being sufficient for complete compensation. The process of solution becomes one of trial and error but presents no serious difficulties. Whichever method be followed, it is possible to arrive at a value of $F(t)$ which, either accurately or approximately, counteracts some particular effect of a gust, and the remainder of the effects, such as that on horizontal velocity and pitching in the illustration, are calculable. It can be shown in a general way that the combined effect of gust and control leads to a reduction of all types of disturbed motion if it leads to a diminution of any one of them. Elimination of an isolated disturbance is practically completed in a time represented by half the period of the slowest oscillation.

The extension of the calculation to a continuously varying wind disturbance follows the lines already covered for non-controlled motion. It again is the case that examples are very few in number, but the advantages of control in steadying the resultant motion of an aeroplane are clearly brought out by this method of attack.

§ (16) Disturbed Motion in Wind.—An illustration of the results of calculations of disturbed motion in a natural wind is given

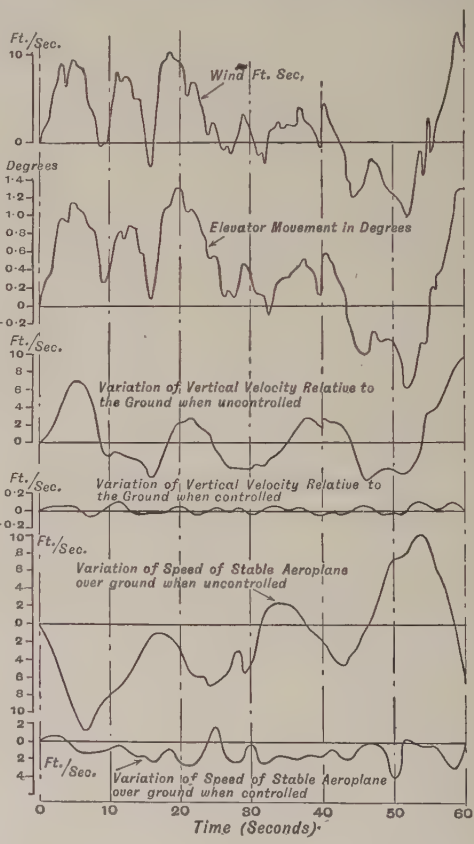

Ft./Sec.
Wind Ft. Sec,
Degrees
Elevator Movement in Degrees
Ft./Sec.
Variation of Vertical Velocity Relative to the Ground when uncontrolled
Ft./Sec.
Variation of Vertical Velocity Relative to the Ground when controlled
Ft./Sec.
Variation of Speed of Stable Aeroplane over ground when uncontrolled
Ft./Sec.
Variation of Speed of Stable Aeroplane over ground when controlled
Time (Seconds).

Fig. 7.

in *Fig.* 7. The upper curve shows the wind speed over the ground as a function of time. Immediately below it is the elevator movement required to eliminate vertical velocity. The lower curves show variations of vertical and horizontal velocities for the conditions of

uncontrolled and controlled flight in the wind represented by the upper curve. The velocity of the aeroplane relative to the air was taken as 80 feet per sec., and it is probable that less marked variations would be found for an aeroplane flying at a greater speed.

The more important references on the subject are:

1. *Stability in Aviation.* Bryan. 1911.
2. *Report of the Advisory Committee for Aeronautics,* 1909 to present date.
3. *Reports of the National Advisory Committee on Aeronautics, U.S.A.*

From (2) can be found the titles and abstracts of contents of articles written in Italy, France, and Germany. Isolated papers appear in the *Journal of the Royal Aeronautical Society.*

L. B.

AIRCRAFT MODEL EXPERIMENTS IN RELATION TO FULL SCALE INVESTIGATIONS

As with many other problems, the form of the equation connecting the forces acting on a body in motion through the air with the size and speed of the body and the properties of the air can be predicted from a consideration of the dimensions [1] of the quantities involved.

For the present we treat the air as incompressible—experiment shows that except when the velocities concerned are very large, approaching the velocity of sound, we are justified in doing this—and we also neglect the effect of the propeller.[2]

The quantities which can affect the motion are the size of the machine and its speed, together with the density of the air and its viscosity; the size of the machine, since we are going to compare the forces on two similar structures, the machine and the model, is sufficiently defined by some length, say the span of the wings;[3] this we denote by l; let v be the velocity of flight, ρ the air density, ν the coefficient of viscosity, R the resistance to motion. Then we may write

$$\begin{aligned} R &= F(\rho, \nu, l, v) \\ &= \Sigma\{\kappa\rho^{\alpha}, \nu^{\beta}, l^{\gamma}, v^{\delta}\}, \text{ say,} \end{aligned}$$

where κ is a numerical coefficient, and F is some unknown function of the variables.

Consider now one term of the series and write down the corresponding dimensional equation. R is a force and its dimensions are MLT^{-2}; the dimensions of ρ are ML^{-3}, of ν, L^2T^{-1}, and of v, LT^{-1}. We thus get

$$[MLT^{-2}] = [M^{\alpha}L^{-3\alpha}, L^{2\beta}T^{-\beta}, L^{\gamma}, L^{\delta}T^{-\delta}].$$

Whence equating the indices of M, L, and T respectively,

$$\begin{aligned} 1 &= \alpha, \\ 1 &= -3\alpha + 2\beta + \gamma + \delta, \\ 2 &= \beta + \delta. \end{aligned}$$

Substituting for α and δ in the second equation it becomes

$$2 = \beta + \gamma.$$

Hence $$\alpha = 1,\ \gamma = \delta = 2 - \beta,$$

and $$R = \kappa\rho l^2 v^2 \left(\frac{\nu}{vl}\right)^{\beta};$$

or since β may have any value we must take account of all possible and write

$$\begin{aligned} R &= \kappa\rho l^2 v^2 \Sigma \left(\frac{\nu}{vl}\right)^{\beta} \\ &= \kappa\rho l^2 v^2 f\left(\frac{\nu}{vl}\right), \end{aligned}$$

where f indicates some unknown function of the variable.[4]

If now we have two similar aircraft differing only in size and speed and R_1, l_1, etc., refer to one, R_2, l_2 . . . to the other, then

$$R_1 = k\rho {l_1}^2 {v_1}^2 f\left(\frac{\nu}{v_1 l_1}\right),$$

$$R_2 = k\rho {l_2}^2 {v_2}^2 f\left(\frac{\nu}{v_2 l_2}\right),$$

assuming the two moving in air of the same density and viscosity. Thus

$$\frac{R_1}{R_2} = \frac{{l_1}^2 {v_1}^2}{{l_2}^2 {v_2}^2} \frac{f(\nu/v_1 l_1)}{f(\nu/v_2 l_2)}.$$

Provided now that

$$f\left(\frac{\nu}{v_1 l_1}\right) = f\left(\frac{\nu}{v_2 l_2}\right),$$

if R_1, etc., refer to the full scale machine, R_2 to the model, then

Force on full scale machine

$$= \text{Force on model} \times \frac{{l_1}^2 {v_1}^2}{{l_2}^2 {v_2}^2}.$$

The condition

$$f\left(\frac{\nu}{l_1 v_1}\right) = f\left(\frac{\nu}{l_2 v_2}\right)$$

will be satisfied if $l_1 v_1 = l_2 v_2$ or if $f(\nu/l_1 v_1)$ is a constant.

Clearly the first alternative is impossible. Since l_2 is much less than l_1, probably about $\frac{1}{20}$ of l_2, v_2 must be much greater than v_1, the air-speed in the tunnel must be (say) twenty times the speed of the machine. Experiment,

[1] See "Dynamical Similarity," Vol. I.
[2] See "Aircraft, Performance of," § (6).
[3] The square root of the area of the wings might conveniently have been taken.
[4] See "Aircraft, Performance of," § (1).

however, shows [1] that for the speeds realised in experiments $f(v/vl)$ is approximately constant, and we are justified, therefore, to a high degree of approximation in writing

$$R = k\rho l^2 v^2$$

and treating the force as proportional to the square of the length of the span and the square of the speed.[2]

Instead of l^2 it is usually more convenient to introduce the quantity S, the area of the wing, which is proportional to l^2, or to treat as the linear dimension involved the square root of the wing area. We thus get

$$R = k\rho S v^2.$$

We may resolve this force into its two components, the one at right angles to the direction of motion, the other in that direction. The first of these is known as the lift, the second as the drag, denoting these by L and D, and we thus find

$$L = k_l \rho S v^2,$$

$$D = k_d \rho S v^2.$$

The quantities k_l and k_d are known as the lift coefficient and the drag coefficient respectively, and it can be shown [3] that if γ is the angle to the horizon at which the aeroplane will glide down in still air with the engine shut off, then

$$\tan\gamma = \frac{k_d}{k_l}.$$

AIRSCREW, THE

§ (1) Introduction. — The present article gives the general outline of the theory of an airscrew. The problem of how an airscrew works is a difficult one, and much of the present knowledge of this subject has been directly obtained from experimental investigations; the theory is necessarily incomplete. For the purposes of reference [4] it should be mentioned that the reports of nearly all the experimental researches made in this country, both with model and with full-scale airscrews, have been published by the Advisory Committee for Aeronautics.[5] Some notion of the state of knowledge of this branch of aerodynamics may be gathered from the fact that, with experience, an airscrew can be designed to give the desired performance within 3 or 4 per cent. The uncertainty of the result will probably be greater if the problem be further complicated by a twisting of the blades under load and, also, if it be necessary to take into consideration the interference on the airscrew performance of the neighbouring parts of an aeroplane.

Some views of a typical two-bladed airscrew, which explain graphically the various terms in common usage, are shown in *Fig.* 1.[6] It will there be seen that each blade section has the characteristic shape of an aerofoil, and also that the blade angle θ, that is, the angle between the chord of the section and the plane of rotation, decreases with an increase of r, that is, of the radial distance of the section from the axis of rotation. An airscrew is said to have *a constant geometrical pitch when θ varies with r in such a manner that $2\pi r \tan\theta$ is a constant.*

Any section of an airscrew by a circular cylinder of radius r having its axis coincident with that of the screw is a helix (*q.v.*), and θ is the angle which the helix makes with a plane perpendicular to the axis. The pitch of the helix, that is, the distance measured parallel to the axis between two consecutive threads, is equal to $2\pi r \tan\theta$, and if this is constant for all sections of the screw, these sections form parts of a series of helices which have the same pitch. We could imagine the face of the airscrew of constant-pitch to be traced out by a straight line at right angles to the axis which revolves uniformly, while one end moves along the axis with uniform speed.

In passing it should, perhaps, be mentioned that the tendency of the present day is to design airscrews with a constant geometrical pitch, since it has been found that, by so doing, the best all-round performance over the range of working speeds is obtained.

The geometrical pitch of a blade element is therefore the forward distance through which the element would advance in one revolution if it were moving in the direction of its chord. We may look on the blade element as a portion of the thread of a screw forming part of a bolt. The geometrical pitch is the distance in the direction of the axis through which any point on this thread would advance when the bolt made one complete revolution in a nut which it fits. An airscrew producing a thrust does not, however, screw itself through the air in precisely the same manner as a nut advances along the axis of the bolt. Excluding frictional forces, the thrust or force acting along the axis of

[1] See "Friction," § (17), *Fig.* 12, Vol. I.

[2] For the modifications required when the effect of the propeller is considered, see "Aircraft, Performance of," § (6).

[3] See Bairstow, *Applied Aerodynamics*, chap. ii. p. 35.

[4] Works which deal exclusively with this subject are: *The Design of Screw Propellers for Aircraft*, by H. C. Watts, published by Longmans, Green & Co.; *Airscrews, in Theory and Experiment*, by A. Fage, published by Constable & Co., Ltd.

[5] Now known as the Aeronautical Research Committee and frequently referred to as A.C.A.

[6] Published by kind permission of Messrs. Longmans, Green & Co.

the nut or bolt arises from the pressures between two solid sliding surfaces; there is a reaction on the nut balancing the forward thrust exerted by the screw. An airscrew, however, works in a medium which readily yields to pressure, so that the whole of the thrust cannot be balanced merely by an increase in the pressure of that medium; such an increase is accompanied by a yielding of the air which acquires a backward momentum. Thus the thrust is the reaction from air which has a general backward motion, and, in consequence of this motion, the airscrew is said "to slip"; the slip increases with the thrust. When an airscrew moves through the air at such forward and rotational speeds that the thrust is zero, this general backward motion disappears; the surrounding air is more or less undisturbed. *The distance moved forward in one revolution at zero thrust is defined as the experimental mean pitch.* The experimental mean pitch is therefore characteristic of the airscrew as a whole rather than of any particular blade element. When an airscrew develops a thrust the forward advance during one revolution is less than the experimental mean pitch, the slip being measured by the difference between these two quantities. The slip ratio is the ratio of the slip to the experimental mean pitch.

§ (2) Airscrew Theory.—Airscrew theory has been developed from two standpoints, firstly, from a consideration of the momentum and energy generated in the slipstream, and, secondly, from the conception that the performance of an airscrew can be determined from an integration of the forces acting on elemental strips of the blade. Later developments involve both these aspects of the problem.

In a momentum theory due to Froude,[1] the airscrew is regarded as an advancing disc of instantaneous change of pressure, and the air is assumed to be both inviscid and incompressible. The dynamic operation of propulsion is considered to depend solely on the reaction resulting from the acceleration of the air, this acceleration taking place both forward and behind the airscrew disc. The rotational motions in the "wake" or outflowing column of air are ignored. *Fig.* 2 gives a diagrammatic representation of such an airflow for an airscrew rotating at a stationary point in a uniform wind of velocity V. In the figure D represents the disc, A and B are sections of the stream well in front of the disc and in the wake respectively. The motion of the inflowing column of air is considered to be due to a negative pressure acting over the

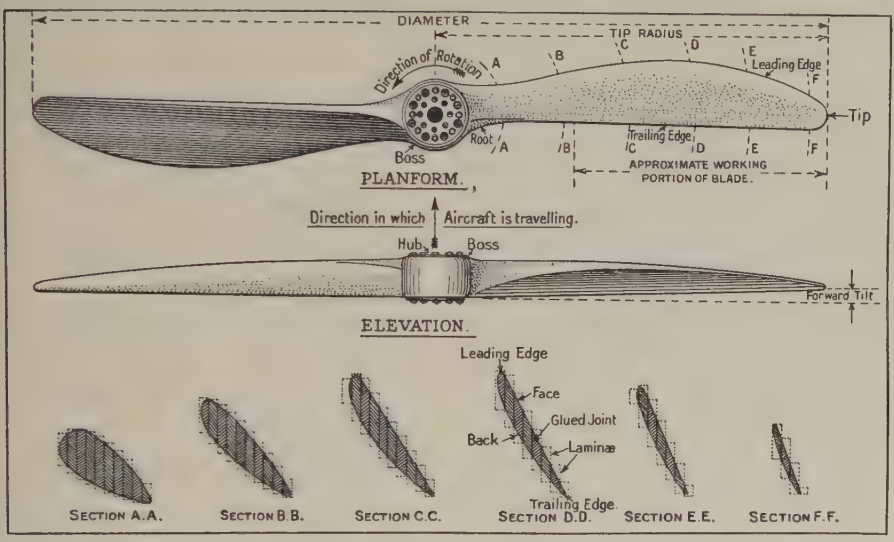


Fig. 1.

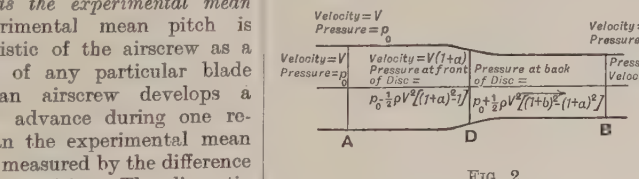


Fig. 2.

[1] On the part played in propulsion by differences of fluid pressure, R. E. Froude, *Trans. I.N.A.*, 1889.

front of the airscrew disc, and is such that the total head is constant along any streamline. At the airscrew disc the pressure head is increased, and as the air flows out it contracts until the pressure is equal to that of the undisturbed air (p_0). The total head in the air surrounding the airstream passing through the airscrew is equal to that of the undisturbed air, whilst the boundary of the stream is considered to be so shaped that the average pressure acting on it in the axial direction is equal to p_0.

The boundary of the airstream passing through the airscrew is therefore a surface of discontinuity. If

$S \equiv$ area of the airscrew disc,

$\rho \equiv$ air density,

$V(1+a) \equiv$ the inflow velocity of the air measured relative to and at the airscrew disc,

$V(1+b) \equiv$ the velocity at the section of the outflowing stream of minimum diameter, measured relative to the airscrew,

then the thrust may be measured either by the difference of pressure on the two sides of the airscrew or by the rate of gain of momentum of the fluid crossing the disc. By equating these two expressions, Froude shows that $b=2a$, that is, a half of the additional velocity found at the smallest cross-section of the outflowing stream is given to the air in front of the airscrew. Moreover, the thrust is equal to the gain of momentum per second of the fluid between A and B. The mass of fluid crossing the disc D per second is $\rho SV(1+a)$ and its total gain of velocity is bV. Hence

$$T=\rho SV^2(1+a)b.$$

We shall now outline a theory, initiated by S. Drzewiecki, in which the thrust and torque of an airscrew are determined from the forces acting on the elements of the blade. Consider an airscrew rotating with a uniform angular velocity Ω, and at the same time moving forward into still air with a uniform axial velocity V. If the air at the front of the airscrew were undisturbed, it can readily be seen from *Fig.* 3 that by virtue of these axial and rotational velocities a blade element at a radial distance r would be moving through the air in the direction OB with a velocity $\sqrt{V^2+(r\Omega)^2}$, where

$$\tan \mathrm{BOA}=\tan \phi_0=\frac{V}{r\Omega}.$$

The air at the front is, however, drawn into the airscrew, so that the blade moves into disturbed air. It is not proposed to consider the general character of this disturbed air; it is sufficient to say that no account will here be taken of pulsations or any irregular rotational motions or eddies other than those which are common to aerofoil flow. We shall assume that the interference flow, or disturbance of flow which affects the aerodynamic behaviour of the blade element, has an axial velocity component aV and a tangential velocity component $a'r\Omega$. The blade element is therefore moving with a velocity $V(1+a)$ cosec ϕ in the direction OC, where

$$\tan \mathrm{AOC}=\tan \phi=\frac{V(1+a)}{r\Omega(1-a')}=\frac{(1+a)}{(1-a')}\tan \phi_0.$$

The air strikes the blade element at an angle of incidence COD, that is $(\theta^\circ-\phi^\circ)$, where θ, the blade angle of the section, is the angle between the chord and a plane at right angles to the axis of rotation, and ϕ represents the angle between the direction of the relative wind and a plane at right angles to the axis of rotation. Assuming that K_L and K_D are the lift and drag coefficients at this angle of incidence, and the chord length and width of the blade element are c and dr respectively, the lift on the blade element $dL=\rho c dr V^2(1+a)^2 K_L \operatorname{cosec}^2 \phi$, and the drag $dD=\rho c dr V^2(1+a)^2 K_D \operatorname{cosec}^2 \phi$.

In *Fig.* 3 the lift dL and the drag dD are represented in magnitude and direction by

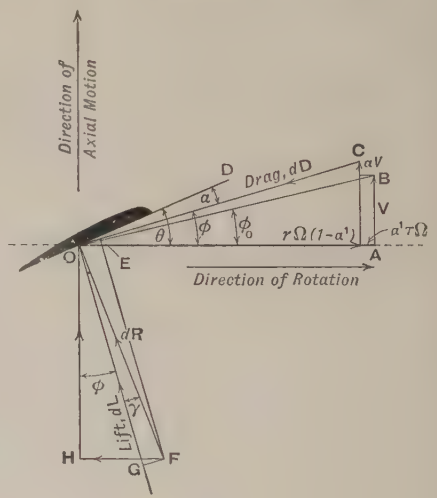


FIG. 3.

GO and EO respectively, so that the resultant force on the blade element is represented in magnitude and direction by FO. The component of this resultant force in the direction of the forward motion is the contribution of the blade element towards the thrust T of

the airscrew. If, then, B represents the number of blades,

$$dT = \rho c dr V^2 B(1+a)^2 \operatorname{cosec}^2 \phi [K_L \cos \phi - K_D \sin \phi],$$

so that

$$\frac{dT}{dr} = \rho c V^2 B(1+a)^2 \frac{K_L \cos(\phi+\gamma)}{\sin^2 \phi \cos \gamma}, \quad (1)$$

where $\tan \gamma = (K_D/K_L)$.

The component in the direction of the rotational motion gives the force opposing the rotation of the element, and when multiplied by the radial distance gives the torque needed to drive the element through the air.

Hence

$$dQ = r \rho c dr V^2 (1+a)^2 \operatorname{cosec}^2 \phi B [K_D \cos \phi + K_L \sin \phi],$$

where Q ≡ the torque of the airscrew, so that

$$\frac{dQ}{dr} = r \rho c B V^2 (1+a)^2 K_L \frac{\sin(\phi+\gamma)}{\cos \gamma \sin^2 \phi}. \quad (2)$$

The thrust and torque of the airscrew are then obtained directly from integration of the thrust and torque grading curves. The representative grading curves of *Fig.* 4 show that most of the thrust is developed and most

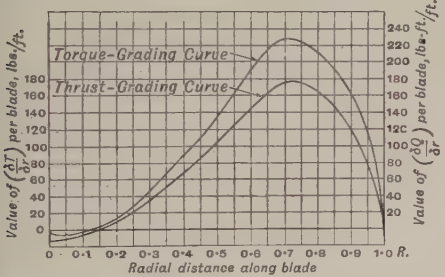


FIG. 4.—Variation of the Thrust and the Torque, along the Blade of an Airscrew which is absorbing 254 h.p. at a rotational speed of 1225 r.p.m. and a forward speed of 90 m.p.h. Diameter of the two-bladed airscrew = 10 feet. Thrust of the airscrew = 805 lbs.

of the torque is expended at the outer part of a blade, which is moving at the higher velocity; also that the maximum values of thrust and torque occur at about 0·7 of the airscrew radius.

The efficiency of working of the blade element

$$= \frac{V[dL \cos \phi - dD \sin \phi]}{r\Omega[dD \cos \phi + dL \sin \phi]} = \frac{V \cos(\phi+\gamma)}{r\Omega \sin(\phi+\gamma)}$$

$$= \frac{(1-a')}{(1+a)} \cdot \frac{\tan \phi}{\tan(\phi+\gamma)}. \quad (3)$$

The above expression shows that the efficiency depends on the values of γ, ϕ, a, and a'.

It can be shown that the efficiency of a blade element has a maximum value when ϕ is about 45°. Further, it is obvious that the efficiency increases with decreases in a, a', and γ, or $\{\cot^{-1}(K_L/K_D)\}$. Generally speaking, the value of ϕ has a smaller influence on the efficiency than the aerodynamic efficiency (K_L/K_D) of the blade section, so that to obtain high propulsive efficiency, the blade sections must have good aerodynamic efficiency. When possible, the angles at the working part of the blade should be large.

The performance of each blade element can only be determined from the expressions (1)-(3) when the values of a, a', K_L, and γ are known. Glauert,[1] in his aerodynamic theory of the airscrew, has given a method for evaluating these quantities. In this theory the airscrew disc is regarded as a disc of pressure discontinuity to account for the thrust, and as a vortex sheet imparting a discontinuity of rotational velocity to account for the torque, but without any direct influence on the radial component of the velocity. Defining the "interference flow" as the disturbance of flow at the airscrew which affects the aerodynamic behaviour of the blade elements, Glauert shows by an interesting application of the Lanchester-Prandtl Theory, firstly, that the interference angular velocity is half of the angular outflow velocity, and secondly, that the interference axial velocity is half the wake velocity. Attention is also directed to the fact that since a and a' represent the whole of the interference experienced by the blade element, the aerofoil characteristics (K_L and K_D) must be those corresponding to infinite aspect ratio. These values of K_L and K_D for the infinite aerofoil can be derived from tests on uniform rectangular aerofoil by the method of the Prandtl Theory.[2] Combining the results obtained from considerations of momentum and from the blade element theory, Glauert shows that $a = F/(1-F)$ to the first order of approximation, and also that $a' = (1+a)F \tan \phi_0 \tan(\phi+\gamma)$, where

$$F = \frac{BcK_L \cos(\phi+\gamma)}{4\pi r \cos \gamma \sin^2 \phi}.$$

These equations, taken in conjunction with those for the thrust and torque of the blade elements, are sufficient to solve completely the problem of the airscrew.

Important characteristics influencing the performance of an airscrew are pitch, number

[1] *An Aerodynamic Theory of the Airscrew*, by H. Glauert, A.R.C. (R. and M., No. 786).

[2] See "Wing Surfaces, Hydrodynamical Theory of," § (3).

of blades, and the ratio of the maximum blade width to the diameter.

Over the usual range of these variables it has been found experimentally that the maximum efficiency of an airscrew increases with the pitch and decreases with an increase of either the number of blades or the blade width. For airscrews of constant plan area and constant pitch the efficiency decreases slightly with an increase of the number of blades or a decrease of blade width.

It is now common practice to design airscrews of constant geometrical pitch, so that the under-surface of each blade forms a true helicoid; this favours a good all-round performance. To eliminate as far as possible any tendency of a blade to twist under load, the outer blade sections are occasionally arranged with the middle points of the chords on a straight line normal to the axis of rotation. Blades tapering in plan form are usually favoured, because for the same performance such an airscrew must have a larger diameter than one with broad blade tips, and so the inflow velocity causing blade interference is smaller; also the region of high slipstream velocity is farther from the body, so that the body interference is smaller.

An airscrew with fixed blades can be designed for only one definite set of working conditions, and when run under different conditions will be less efficient than an airscrew designed specially for these conditions. On the other hand, the performance of a variable-pitch airscrew is the envelope of the performances of airscrews designed for special purposes, and so favours at all flight speeds a good over-all efficiency of the combination of engine and airscrew. It has been shown experimentally that the efficiency of a variable-pitch airscrew obtained by rotating the blades of an airscrew of medium pitch compares favourably with that of the corresponding series of airscrews of constant geometrical pitch.

The preceding theory takes no account of the modification of the performance of an airscrew due to the presence of the aeroplane. From a theoretical standpoint it may be considered that an effect of the aeroplane is to slow up the wind in the neighbourhood of the airscrew boss, so that to develop at the same rotational speed, either the same thrust or the same torque, the forward speed of the airscrew relative to the undisturbed air needs to be increased. Experimental evidence shows, however, that the interference effect is not entirely of a "slowing-up" nature, since the same increase of forward speed is not sufficient to maintain constant both the thrust and torque. If at the same values of the thrust and the rotational speed a comparison be made between the performance of the airscrew with and without the aeroplane interference, it follows that in the former case the airscrew is doing more useful work, although the increase of efficiency is not as large as would be expected from the increase of forward speed, because, owing to an increase of torque, the horse-power absorbed is also greater. An analysis of the data of several experiments made to measure the magnitude of the interference effect of an aeroplane on the performance of an airscrew shows that at any forward speed the presence of the aeroplane increases both the thrust and the efficiency and reduces the rotational speed of the airscrew. Also the extra resistance of the body due to the airflow around the airscrew is greater than the increase of thrust of the airscrew due to the interference of the body, so that the mutual interference of the airscrew and the body adversely affects the over-all efficiency of the entire aeroplane.

The preceding theory does not take into consideration any deformation of the blade under load, which is probably the principal cause of any discrepancy between the estimated and practical performances of an airscrew. It should also be borne in mind that, in view of the limitations imposed by practical considerations, the design of an airscrew is not exclusively an aerodynamic problem.

§ (3) The Airflow around an Airscrew.—It is now proposed to consider the nature of the airflow around an airscrew. Firstly, we shall consider the flow of the air at the front of the airscrew, then what is occurring at the airscrew disc, and finally the flow of the air after leaving the airscrew. Nearly all the present knowledge of the airflow around an airscrew, and also what is taking place at the airscrew blades, has been obtained directly from experimental researches. It is, however, a matter of some difficulty to measure with great accuracy in the region surrounding an airscrew either the velocity or the pressure, since both are varying continuously from point to point. It has already been mentioned that when an airscrew is developing a thrust the air at the front is disturbed in such a manner that it is drawn into the front, or, in other words, the velocity of the airscrew relative to the air immediately in front is greater than that measured relative to the undisturbed air. At any instant, the total axial inflow velocity, that is, the difference between the instantaneous axial velocity and the velocity of the undisturbed air, is not uniform, but depends on the position relative to the blades. Also, at any point fixed relative to the plane of rotation, the total axial inflow velocity varies periodically from a maximum somewhere in the neighbourhood of a blade to a minimum somewhere between two consecutive blades. It has been found experimentally that the total head, that is, the sum of the velocity and pressure heads, has a constant value at all points of the inflowing stream, so that as the air advances towards the airscrew disc, the progressive increase of velocity head is accompanied by an equal decrease of pressure head. In addition to the axial motion, the inflowing air has a radial velocity, often of appreciable magnitude,

When passing through the airscrew the air receives a large increase of pressure head and some small increase of velocity head. It is, of course, obvious that if we knew the distributions of pressure and of velocity, the thrust of the airscrew could be estimated from the sum of (*a*) the integral of the pressure differences, and (*b*) the change of the axial momentum of the air in passing from the front plane to the back plane of the airscrew, these two planes being taken as close to the airscrew as possible. Unfortunately, it is difficult to measure with good accuracy either the pressure or the velocity. Measurements of total head can, however, be easily made, and it has been found [1] that over the ordinary working range of an airscrew the total thrust may be estimated with good accuracy from the distribution of total head measured immediately behind the airscrew; the total head of the inflowing stream being taken as datum. The accuracy of this method of measuring the thrust is due essentially to the fact that there is little change of velocity of the air when passing through the airscrew. With the airscrew rotating at a stationary point this method of measuring the thrust is not so reliable. Some idea of the nature of the airflow around an airscrew blade may be gathered from an analysis of the distribution of pressure over the blade surface. Such an investigation has been made by Fage and Howard [2] at the National Physical Laboratory. It is, of course, impossible to describe this investigation in any detail. The experiments were made with a model airscrew of diameter 3·9 ft. mounted in a 7-ft. wind channel in front of a cylindrical body of diameter 1·1 ft. The diagrams of *Figs.* 5 and 6, which are fairly representative, show at several working conditions of the airscrew the distributions of pressure over a blade element situated at a radial distance $r = 0{\cdot}75R$. By comparisons with the pressure distribution over corresponding aerofoils, it was found that the general shape characteristics of each of these pressure diagrams are very similar to those of an aerofoil of the same section. It is of interest to note that the thrust of the airscrew as calculated from the distribution of pressure over the blade surface agreed within 1 or 2 per cent with the measured value, whilst the calculated torque, which does not take into account surface friction, was about 86·5 per cent of the measured value. With the

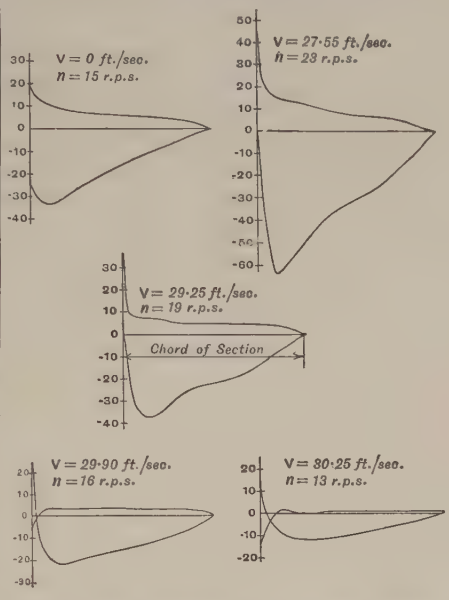


FIG. 5.—Pressure Distribution over a Blade Element. Section at $r = 0{\cdot}75R$. Ordinates are pressures in lbs. per sq. ft. Area of each figure is proportional to the force normal to the chord.

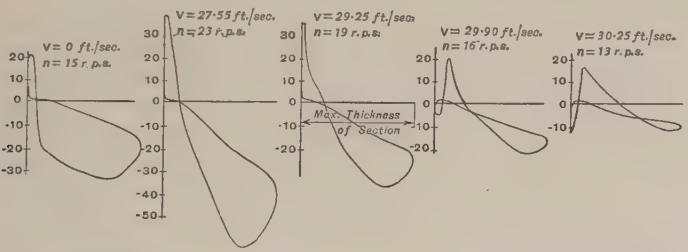


FIG. 6.—Pressure Distribution over a Blade Element. Section at $r = 0{\cdot}75R$. Ordinates are pressures in lbs. per sq. ft. Area of each figure is proportional to the force parallel to the chord.

[1] *On the Method of Estimating from Observation, on the Slip Stream of an Airscrew, the Performance of the Elements of the Blades, and the Total Thrust of an Airscrew*, T. E. Stanton and D. Marshall, Advisory Committee for Aeronautics, 1918.

[2] *An Investigation of the Distribution of Pressure over the Entire Surface of an Airscrew Blade*, by A. Fage and R. G. Howard, Aeronautical Research Committee, June 1920.

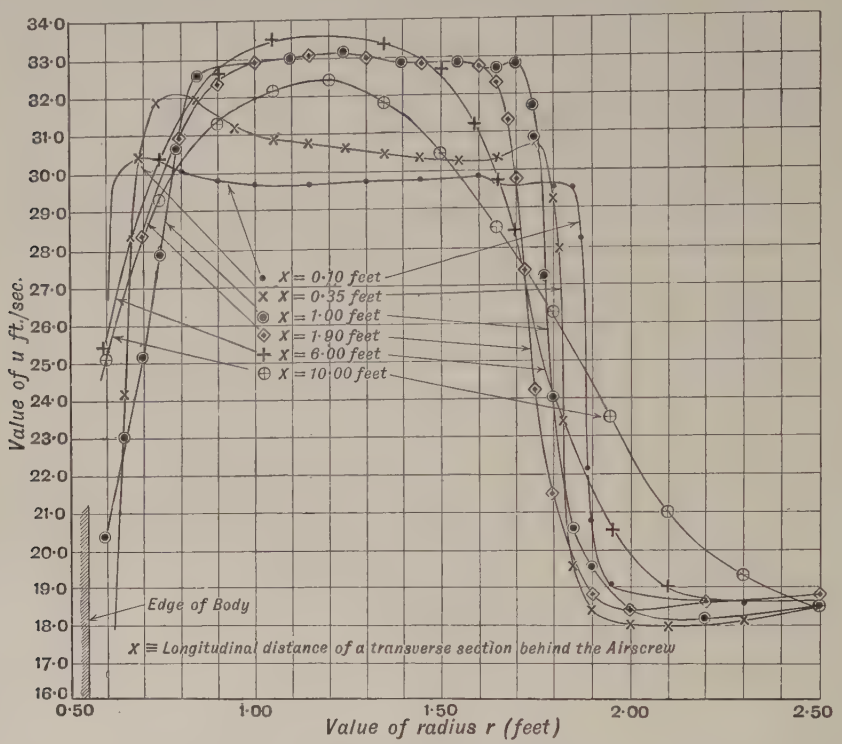

Value of u ft./sec.
Value of radius r (feet)
X = 0·10 feet
X = 0·35 feet
X = 1·00 feet
X = 1·90 feet
X = 6·00 feet
X = 10·00 feet
Edge of Body
X ≡ Longitudinal distance of a transverse section behind the Airscrew

FIG. 7.—The Airflow around an Airscrew. Distribution of axial velocity in the outflowing stream. T = 10 lbs., V = 18·6 ft./sec., n = 14·8 r.p.s., D = 3·9 ft.

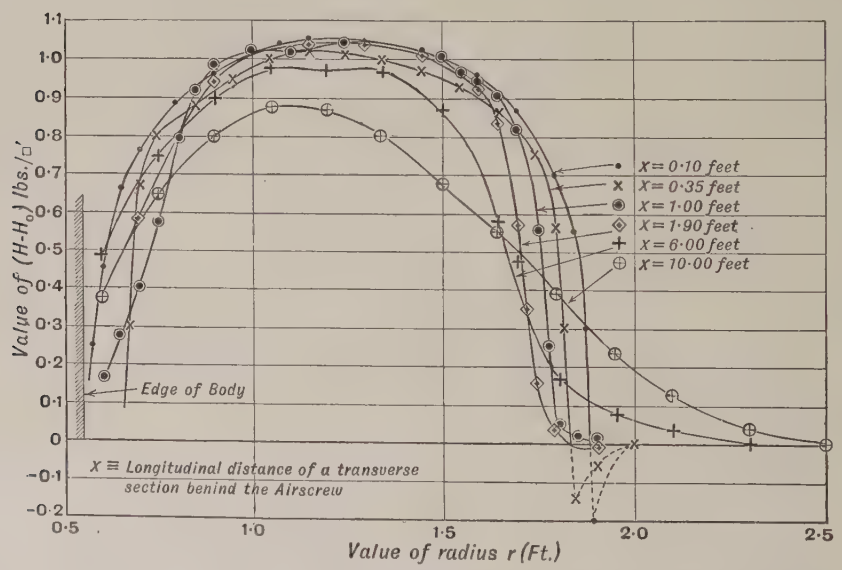

Value of (H-H₀) lbs./□'
Value of radius r (Ft.)
X = 0·10 feet
X = 0·35 feet
X = 1·00 feet
X = 1·90 feet
X = 6·00 feet
X = 10·00 feet
Edge of Body
X ≡ Longitudinal distance of a transverse section behind the Airscrew

FIG. 8.—The Airflow around an Airscrew. Distribution of total head in the outflowing stream. T = 10 lbs., V = 18·6 ft./sec., n = 14·8 r.p.s., D = 3·9 ft. Datum total head represented by H_0.

same airscrew, experiments [1] were also made to measure the distribution of pressure and velocity around the airscrew. The curves of *Figs.* 7, 8, and 9, which have been drawn from these experimental data, may be regarded as

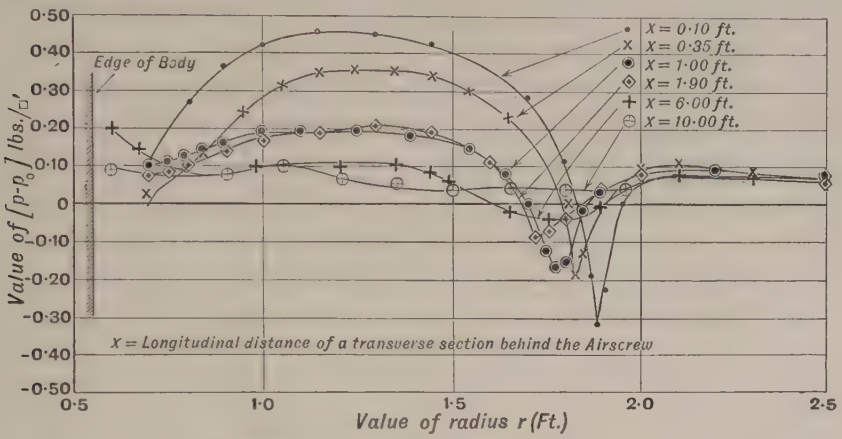


FIG. 9.—The Airflow around an Airscrew. Distribution of pressure in the outflowing stream. T = 10 lbs., V = 18·6 ft./sec., n = 14·8 r.p.s., D = 3·9 ft. Datum pressure represented by p_0.

the outflowing stream is seen to be fairly constant. From the data of these velocity curves it is a simple matter to calculate the shape of the boundary surface of a "constant-volume" column, that is, a column such that

showing fairly representative distributions of total head, velocity, and pressure in the outflowing stream.

It is seen that at any cross-section of the outflowing stream, which is situated within 0·5D from the airscrew, the velocity distribution is fairly uniform, except near the body and the boundary, where the velocity gradients are very pronounced. Also these curves, taken

a constant volume of air flows in unit time through any cross-section. The shapes of the generating lines of the boundary surfaces of such "constant-volume" columns are shown in *Fig.* 10, where it will be noticed that the columns have an outward bulge in the neighbourhood of the edge of the body, and also a pronounced inward bulge at the periphery of the blade tips, which is probably a region of

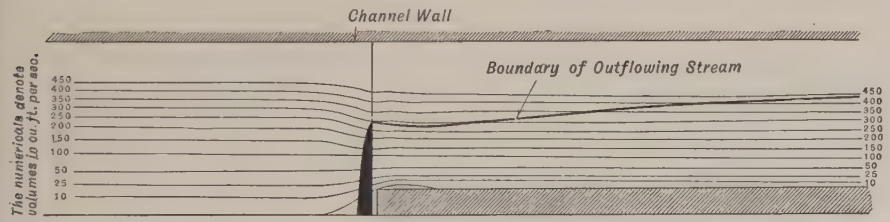


FIG. 10.—The Airflow around an Airscrew. Diagram showing the boundary lines of columns which are such that with any one column a constant volume of air flows in unit time through any cross-section. T = 10 lbs., V = 18·6 ft./sec., n = 14·8 r.p.s., D = 3·9 ft.

in sequence, show that the average velocity of the air in the outflowing stream first increases rather rapidly to a maximum and then slowly decreases as the stream opens out. Also the velocity of the stream surrounding

vortex motion. The thick line of this diagram represents the boundary of the outflowing stream as measured from the total-head experiments. Actually, the boundary of the outflowing stream is not a line but a sleeve of eddying motions, and so is somewhat difficult to locate accurately. It is seen that up to the section of minimum diameter, the area of which will vary with the thrust, the volume of air flowing through any cross-section of

[1] *An Experimental Investigation of the Nature of the Airflow around an Airscrew in order to determine the Extent to which the Airflow assumed in the Momentum Theory of Froude is realised in Practice*, A. Fage and R. G. Howard, Advisory Committee for Aeronautics, 1919.

the outflowing stream is more or less constant, but beyond this section the outflowing stream widens considerably as more and more air is dragged on by the discharged stream.

In addition to the axial motion, the discharged air has a general rotational motion in the same direction as the airscrew, and also the inevitable irregular motions or eddies. As would be expected, owing to the intermittent action of the blades, both the translational and rotational velocities with which the air is discharged are not uniform, but periodic in magnitude. Generally speaking, the structure of the outflowing stream—where the air discharged from a blade element intermingles with that of the neighbouring annuli columns—is analogous to the twisted strands of a rope.

The curves of *Fig.* 8 show the distribution of total head at the several sections of the outflowing stream, when the datum total head is measured at a point sufficiently far in front of the airscrew to be without the disturbance due to the working of the airscrew. As mentioned elsewhere, it was found that the integral, taken over the airscrew disc, of the difference between the total head at points in two planes as close to the disc as convenient, one in front and one behind, is equal to the thrust of the airscrew. The curves of distribution of pressure—*Fig.* 9—show that as the air flows outward, the pressure falls rather rapidly at first, and then becomes more or less of constant magnitude beyond the section of minimum diameter. The pressure gradients at the body, and specially at the boundary of the outflowing stream, are fairly pronounced.

In practice, the close proximity of the aeroplane will modify the airflow around the airscrew. With the present method of design some part of the tail is usually within the outflowing stream, so that both the stability and the controllability of an aeroplane will depend on the airflow around the airscrew. With a single-engine tractor aeroplane the outflowing stream is divided by the wings and body into three parts, one part being beneath the lower wing. As each part of the outflowing stream moves away from the airscrew disc it has a general deflection in the direction of rotation. Also, the outflowing stream as a whole is deflected by the downwash from the wings and the general attitude of the aeroplane relative to undisturbed air.

§ (4) Discussion of the Performance Data of a Representative Airscrew.—The present article would be incomplete without a consideration of the performance of a representative airscrew. Standard methods of measuring the performance of a model airscrew are described in Vol. I.[1] A universal method of presenting the performance data of an airscrew is in terms of the quantities

$$\left(\frac{T}{\rho n^2 D^4}\right), \left(\frac{Q}{\rho n^2 D^5}\right), \left(\frac{V}{nD}\right), \text{ and } \eta,$$

where $V \equiv$ the forward speed of the airscrew in ft./sec.

$D \equiv$ the diameter of the airscrew.

$n \equiv$ the rotational speed in r.p.s.

$T \equiv$ the thrust in lbs.

$Q \equiv$ the torque in lbs.-ft.

$\rho \equiv$ the density of the air in slugs per cubic ft. (At a temp. of 15·6° C. and pres. 760 mm. $\rho = 0{\cdot}00237$ slug per cubic ft.)

and $\eta \equiv$ the efficiency = useful work done/total work supplied $= (VT/2\pi Qn)$.

As shown elsewhere, the forces on an aerofoil depend on its area, the square of its speed relative to the air, and the density of the air. In the case of an airscrew considered as composed of a number of aerofoils the area varies as D^2, whilst the speed relative to the air at any point depends on the forward velocity V, and the velocity due to the rotation which varies as nD. So long, then, as V/nD is constant the square of the speed relative to the air is proportional to n^2D^2. The forces on the airscrew consist of a thrust parallel to the direction of advance and a tangential force at right angles to this; the arm at which this latter force acts is proportional to D. These forces are proportional to the square of the speed measured by n^2D^2 and the area of the propeller which varies as D^2; thus we have for the thrust and torque respectively the expressions

$$\begin{aligned} T &= k_t \rho D^2 n^2 D^2 \\ &= k_t \rho n^2 D^4, \\ Q &= k_q \rho D^2 n^2 D^2 D \\ &= k_q \rho n^2 D^5, \end{aligned}$$

where k_t and k_q are numerical coefficients which have the same values for any system of consistent units.

But this is only true so long as V/nD is constant. Thus we have also $V = k_v nD$.

The coefficients k_t and k_q depend on the angle of attack α and the ratio V/nD, which has been assumed to be constant; they may be expressed as functions of these quantities in the form $\psi(\alpha, V/nD)$ and $\chi(\alpha, V/nD)$. For a fuller discussion reference should be made to the article "Aircraft, Performance of," §§ (4) and (6).

Hence the quantities

$$\left(\frac{T}{\rho n^2 D^4}\right), \left(\frac{Q}{\rho n^2 D^5}\right), \left(\frac{V}{nD}\right),$$

which are equal to k_t, k_q, and k_v respectively, form a series of non-dimensional coefficients

[1] See "Dynamometers" (Airscrew), § (7), Vol. I.

in terms of which the performance can be expressed. The above assumes (i.) that the airscrew is not distorted by the motion, and (ii.) that its top speed does not approach the velocity of sound.

With these non-dimensional coefficients,[1] it follows that V, n, T, Q, and ρ can be measured in any system of consistent units.

The curves of *Fig.* 11 completely define the performance of a representative airscrew of

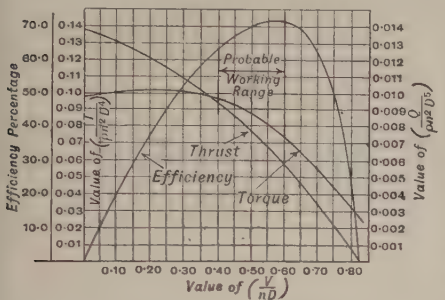


FIG. 11.—Performance Curves of a Representative Airscrew.

which the ordinary working range is from $(V/nD) = 0{\cdot}4$ to $(V/nD) = 0{\cdot}6$. It will there be seen that the thrust coefficient has its maximum value when the airscrew rotates at a stationary point, and a zero value when $(V/nD) = 0{\cdot}82$, in which case the forward advance per revolution is equal to the experimental mean pitch. With an increase from the zero value of (V/nD) the torque coefficient at first increases very slightly and afterwards decreases very rapidly. The hump in the torque curve would probably be more pronounced in the case of an airscrew with larger blade angles. Obviously the airscrew has zero efficiency when $(V/nD) = 0$, since $V = 0$, and also when $(V/nD) = 0{\cdot}82$, in which case $T = 0$. From the diagram it will be seen that at any value of (V/nD) the airscrew has only one value of efficiency. The maximum efficiency is 72·0 per cent, and occurs when $(V/nD) = 0{\cdot}60$. From experiments made with a model of this airscrew it was found that at any value of (V/nD) both the thrust and the torque were each proportional to either the square of the rotational speed or the square of the translational speed. Also, with the airscrew rotating at a stationary point, both the thrust and the torque were each proportional to the square of the rotational speed.

It can be easily shown from the data of these curves that if the rotational speed be maintained constant an increase of forward speed will be accompanied with a decrease of thrust; also, if the thrust be maintained at a constant value, an increase of forward speed is accompanied with an increase of torque.

In practice, the performance of an airscrew depends on the characteristics[2] of both the engine and the aeroplane. With the engine working all-out the airscrew develops its maximum thrust when the aeroplane is held fixed on the ground; with an increase of forward speed the thrust decreases, and the rotational speed increases. Although the thrust at climbing is greater than that at a higher forward speed, the thrust horse-power is smaller, firstly, because of the loss of efficiency of the airscrew, and secondly, because of the drop of B.H.P. due to the slowing-up of the engine. When designing an airscrew due consideration should be given to the characteristics of both the engine on which it is mounted and the aeroplane it is to drive. Thus, with a scout machine which has to fly for long periods at its maximum speed, the best possible combination of engine, airscrew, and aeroplane would be that with which the engine gave its maximum horse-power and the airscrew its maximum efficiency at the maximum flight speed of the aeroplane. On the other hand, if climbing were the first essential, the engine should give its maximum horse-power and the airscrew its maximum efficiency at the climbing speed of the aeroplane. Usually a compromise is made so that the maximum horse-power of the engine and the maximum efficiency of the airscrew are developed at a forward speed somewhere intermediate between the climbing speed and the maximum flight speed. In such a case an endeavour would be made to make the efficiency and horse-power curves as flat as possible, so that the efficiency of the airscrew and the horse-power of the engine, both at climbing and at the maximum speed, are not greatly different from their maximum values.

A. F.

AIRSHIP FABRIC, DETERIORATION OF, AND ITS PREVENTION. See "Airship Fabrics," § (4).

AIRSHIP FABRICS

I. TENSILE PROPERTIES

§ (1) NON-RIGID ENVELOPE FABRICS.—Tension in the fabric is due to the internal pressure (about 30 mm. of water) which is maintained in the envelope in order to preserve its shape, and at certain points there is, in addition, a tension induced by the rigging.

The fabrics are of cotton and are built up with intermediate layers of rubber from cloths

[1] See "Dynamical Similarity, Principles of," Vol. I.

[2] See "Aircraft, Performance of."

selected (in the case of British airships) from the following standards:

Quality.	Wt. Gm./M.².	Tensile Strength, Kgs./M.
A . .	130	1250
B . .	110	1100
BX . .	90	900
C . .	80	800
D . .	65	650

They are nearly identical in specific strength, all having a breaking length of 10,000 metres. The strengths stated are specified minima for warp and weft in the "grey" state.

Single-ply fabrics are not used in envelope construction largely on account of the loss of strength from small local defects. Two-ply fabric is most usual, and three ply is used where exceptionally heavy stresses are involved. Two- or three-ply fabrics may be parallel or more usually diagonally doubled. In the latter case one ply, the lighter if the plies are unequal, is laid with its yarns at 45° to those of the straight ply. In this case the diagonal ply confers the valuable property of greatly increased resistance to bursting and to tearing when the stressed fabric is wounded.

§ (2) Detailed Tests. — Experiment on these two types of two- and three-ply fabric has been directed to the following points:

(i.) The relation of the simple tensile strengths of compound fabrics to those of their components.

(ii.) The strength of wounded fabrics.

(iii.) The relation between simple tensile test and various forms of compound stress test, including bursting, for unwounded and wounded fabrics of different types.

(iv.) The effect of sustained load.

(i.) *Tensile Tests.*—The above table gives the results of simple tensile tests on a number of two-ply fabrics made from the cottons specified above. The letters in brackets denote diagonal ply. The breaking load for a diagonally doubled fabric is that at which the straight ply breaks down.

T = strength of the compound fabric.
t_1 and t_2 = strengths of straight and bias plies separately.

Numerals in brackets denote values not experimentally determined but assumed from the specification of the cloth. The values given are typical ones, but no general formula applicable to all diagonal fabrics can be deduced from them.

In columns 6 and 7 the mean value of t_2 for warp and weft is used.

If the numbers in columns 6 and 7 be compared it will be seen that there is a variable difference between them, this being related to the support in simple tension given to the straight ply by the biassed. The simple tensile test on a bias doubled fabric is, of course, a very unreal one, bearing no relation to the conditions of stress obtaining in practice. It is useful, however, as a rough guide.

1. Structure of Fabric.	2. Direction.	3. $\frac{T}{\text{Kilos./Metre}}$.	4. $\frac{t_1}{\text{Kilos./Metre}}$.	5. $\frac{t_2}{\text{Kilos./Metre}}$.	6. $\frac{T}{t_1+t_2}$.	7. $\frac{t_1}{t_1+t_2}$.
A (D) . .	Warp	1560	(1250)	(650)	·82	·66
B (C) . .	Warp	1306	(1100)	(880)	·69	·56
B (C) . .	Warp	1183	980	626	·75	·62
	Weft	1234	1080	580	·73	·64
C (C) . .	Warp	1025	800	844	·64	·50
	Weft	932	653	753	·64	·45
D (D) .	Warp	742	635	553	·60	·56
	Weft	707	562	463	·58	·53
BX (BX) .	Warp	1000	625	852	·69	·43
	Weft	1000	635	800	·69	·43
CC parallel	Warp	1705	(800)	(800)	1·06	·5
	Weft	1580	(800)	(800)	·99	·5

(ii.) *Wounded Fabrics.*—The tearing strength of a wounded fabric in simple tension is defined as the quotient

$$\frac{\text{Load to produce tearing}}{\text{Width of test piece}}.$$

It has been shown that for a given fabric it is determined by the size of the wound and is independent of the dimensions of the test piece, *provided* the latter includes the region of non-uniform stress distribution which the wound causes, the so-called danger rectangle.

The important differences, in respect of this property, between various fabrics are shown in the following results of tearing tests. The wounds were straight cuts placed centrally at right angles to the direction of stress. The test pieces were in most cases 6 in. wide and 20 in. effective length.

The column headed *b/s* gives the ratio strength of bias ply/strength of straight ply. The low tearing strengths of single ply and

parallel doubled fabrics are noteworthy. The high tearing strength of diagonal fabrics is shown and also its increase with increase in the value of the ratio b/s.

Fabric.	Tearing Strength as per cent of Full Strength.			$\frac{b}{s}$
	½ In. Cut.	1 In. Cut.	1½ In. Cut.	
1-ply proofed C	40	22	19	..
CC parallel	33	24	18	..
2-ply parallel (not a standard fabric)	41	27	22	..
B (D)	57	46	41	·59
B (C)	62	45	..	·73
C (C)	72	59	51	1·0
D (B)	79	69	63	1·7
C (C) C	50	35	..	·5
(C) C (C)	88	..	..	2·0

(iii.) *Compound Stress Tests.*—These have been made in three principal ways.

(*a*) By attaching weights to a cross-shaped test piece the central square is placed under compound stress, variable at will. Few results are available by this method, which in any case has several drawbacks, notably that enhanced stresses exist near the corners of the test square, so that the stress at the middle of the square is different by an unknown amount from that calculated as the quotient of the load by the width. A parallel doubled fabric thus tested for tearing strength gave results close to those obtained by tearing in simple tension (Booth, *A.C.A. Reports*, May 1911, T, 111).

(*b*) Cylinders of fabric 5 in. diameter and 30 in. long with metal end plates were subjected to air-pressure which sets up a circumferential and a longitudinal tension, the latter being further increased by loading the cylinder held between the grips of an Avery testing machine. In other tests, cylinders of approximately this size were subjected to bursting pressure but without additional longitudinal tension. By these two kinds of bursting tests with small cylinders the values found for the ratio

$$\frac{\text{Tensile strength by bursting}}{\text{Simple tensile strength}}$$

were 1·4 to 1·6 for various diagonally doubled fabrics, 0·6 to 1·06 for parallel doubled, and about 0·7 for single ply.

(*c*) Bursting tests on larger models. Avorio (quoted in *A.C.A. Report*, 1913–14, p. 434) tested a variety of two-ply diagonal and parallel fabrics in the form of cylinders with hemispherical ends.

Up to 1·0 metre diameter decrease in bursting stress accompanied increase of diameter. From 1·0 m. to 3·4 m., the largest cylinder tested, there was no further decrease. From the minimum results the ratio bursting stress to ultimate simple tensile stress was found to be 0·63 and 1·00 for parallel and diagonal two-ply fabrics respectively. To what extent the discrepancy between these figures and those in (*b*) is accounted for by the scale effect seems doubtful in view of the results obtained in bursting tests on large model envelopes (see succeeding section).

(*d*) More recently in this country tests on diagonal and parallel two-ply fabrics have been made, using a model 20 ft. long, of the envelope of the S.S. type of non-rigid airship. Complete gores of the fabric under test were inserted by means of stuck seams in an envelope made of strong three-ply fabric. Measurements of circumference at burst and of bursting pressure were made, using in turn gores of the different fabrics named both whole and variously wounded at the maximum diameter. There were no transverse seams and the weft yarns took the circumferential tension. For comparison with these results simple tensile tests on whole and wounded pieces were made in the weft direction of the same three fabrics. The results in kilogrammes/metre are given in the following table.

T_b = bursting stress.
T_t = breaking stress in simple tension.

Fabric.	No Wound.	½ In. Hole.	¾ In. Hole.	¾ In. Slit.
		T_b Kilos./Metre.		
C (C)	1110	1115	1007	825
B (D)	1366	1004	920	..
CC parallel	1130	513	435	340
		T_t Kilos./Metre.		
C (C)	996	707	650	620
B (D)	1140	715	664	620
CC parallel	1250	604	500	423
		Ratio T_b/T_t.		
C (C)	1·11	1·58	1·55	1·33
B (D)	1·20	1·40	1·38	..
CC parallel	·90	·85	·87	·80

These results show the superiority of the diagonal fabrics over the parallel, and the misleading indications of simple tensile tests. These three fabrics were of almost identical weight, viz. about 350 gm./m.^{2}, about 180 of which was cotton. The strength figures as they stand are therefore proportional to specific strength. The symmetrical fabric C (C) has a slight superiority over the B (D) for small wounds, but there is an indication that with larger ones this would be lost. It will be observed that these results stand between Avorio's (see (iii.) (*c*)) and those

quoted in (iii.) (*a*) and (*b*). Few, if any, comparative bursting and tensile tests seem to have been made in which all the conditions affecting the results have been controlled or even observed. Scale effect, number of seams, humidity, temperature, and rate of loading have all to be considered. The rate of loading is very important for the comparison, because it has a very marked effect on the apparent breaking load of two-ply fabrics in simple tension. Differences of the order of 10 per cent and 20 per cent for diagonal and parallel two-ply fabric respectively may be found for rates of 30 and 150 lbs./in./min., the higher rate giving the greater apparent strength. Bursting tests probably correspond to slow loading. In the comparative data in the above tables the tensile figures are also for slow loading. For the higher rate of 150 lbs./in./min. they would have been 10 per cent to 20 per cent higher and the ratio T_b/T_t correspondingly decreased.

(iv.) *Sustained Loads.*—A few experiments have been made on the behaviour of fabrics under sustained load. The results, which are of only preliminary character, exhibit a property of the material very important in envelope construction and worth further study.

Below are given some results on plain B cotton and on a number of other fabrics.

B cotton. Warp direction. Normal breaking load tested at 72 per cent humidity and 150 lbs./in./min. = 129 lbs./2 in.

Load applied. Lbs.	Per cent of Normal Breaking Load.	Time to Break.
116	90	1 or 2 seconds.
110	85	A few seconds.
103	80	8 to 13 minutes.
96	75	1 to 2 hours.

Fabric.	Approximate Normal Breaking Load. Kilos./Metre.	Sustained Load. Kilos./ Metre.	Percentage of Normal Breaking Load.	Time to Break (Days).
C(C)C warp . .	1900	950	50	5
BD parallel warp	1460	900	62	5
BD biassed warp	1310	680	52	7
Single ply linen (120 gm./m.)	1100	620	56	5

Portions of the broken fabrics re-tested in the ordinary way had a breaking stress much higher than the sustained stress under which the fabric broke, and often only very little lower than that of the new material. This behaviour of fabrics under continued loads much lower than the usually accepted breaking load clearly introduces a new corrective to the estimates made of the strength of the fabric under working conditions and calls for further experimental study.

In conclusion, it should be mentioned that the effect of rise of temperature in temporarily lowering the strength of cotton fabrics does not seem, in view of the use of airships in tropical climates, to have received sufficient attention. Two separate parts of this effect must be distinguished, viz. the pure temperature effect and the effect of lowered humidity of the fabric. The latter is well recognised, but it appears from some tests on two-ply fabrics that between the temperatures 12° and 30° and 40° Centigrade there is a decrease in strength roughly double that usually ascribed to the lowered humidity. The two effects together account for a total decrease at 50° C. of about 30 per cent of the strength at 12° C.

§ (3) Rigid Airship Fabrics. (i.) *Outer Covers and Gas-bags.*—Experimental work on these two important classes of fabric has not dealt with their tensile properties so much as with their durability. The strength requirements seem scarcely to have been analysed. The strengths of the fabrics in a rigid airship are not a measure of the strength of the ship. The requirements of an outer cover in many respects resemble those of aeroplane wing coverings (see article "Aeroplane Textiles").

The stresses to which gas-bags are exposed are very indeterminate, the greatest possibly being those connected with the actual handling of the bag when placing and adjusting in position in the ship. Gas-bags are usually of D quality cotton (see above). The goldbeater's skin which secures gas-tightness also contributes to the tensile strength. It may also considerably improve the tearing strength, but whether it does so or not depends on the mode of its adhesion to the cotton.

The following are typical figures for two types of skin-lined fabric:

Type.	Tensile Strength. Kilos./Metre.		Tearing Strength for ½ in. Cut, as Percentage of Unwounded Strength.	
	Warp of Cotton only.	Warp of whole Fabric.	Warp of Cotton only.	Warp of whole Fabric.
Rubber-stuck skin-lined fabric	670	825	40	65
Glue-stuck skin-lined fabric	608	860	40	40

It may be added that some of the mechanical properties of the fabric, *e.g.* equal extensibility of skin and textile under various conditions, are even more important for retention of gas-

holding properties than for maintenance of strength.

Bibliography

Reference may be made to the following papers published by the Advisory Committee for Aeronautics. *Reports and Memoranda*, Nos. 23, 29, 37, 180, 182; also Nos. T. 111, 167, and 1204.

For description of machines and methods used in tensile tests on fabrics see this Dictionary, article on "Aeroplane Wings, Fabrics for."

II. Deterioration and its Prevention

§ (4) Non-rigid and Kite Balloon Fabrics.—These are normally of two-ply or three-ply rubber proofed cotton. They are built up with rubber between the plies of cotton. One ply is often laid with its yarns diagonal to those of the main plies which take the direct tension. This diagonal ply distributes the concentration of stress which would otherwise arise at the end of a cut, and by so doing greatly increases resistance to tearing (see article, "Aeroplane Wings, Fabrics for"). One layer of rubber is usually made 100 gm./metre^2 to constitute a gas-tight layer; 30 gm./metre^2 is sufficient for the adhesion of plies and is used between the two outer plies of a three-ply fabric. On the outside surface there is either camouflage colouring or a special rubber layer to give protection against weather.

The rubber proofing differs somewhat in composition with different makers. The gas-holding layer is normally at least 95 per cent hard fine Para rubber with from 1 to 3 per cent of sulphur and small amounts of litharge, lime, magnesia, or organic substances as accelerators of vulcanisation. These represent average British practice for heat-cured fabrics.

In service both the rubber and the cotton decay under the action of light, heat, and tension. The former is by far the most active cause of deterioration.

The action of light on cellulose in the form of linen thread has been studied by Aston (*A.C.A. Reports and Memoranda*, No. 396). The conclusions reached, which doubtless apply also to cotton, are that visible light has scarcely any effect, the active radiation lying in the spectral region between about 4000 and 2950 A.U., and that the presence of oxygen greatly increases the rapidity of attack. The products of the destructive action of ultra-violet light on cotton, in the air, have the properties of the oxycelluloses (Doree and Dyer, *Journ. Society Dyers and Colourists*, Jan. 1917). It is impracticable to protect the cotton from oxygen, but it can be more or less completely shielded from light. This, however, does not complete the preservation of the fabric.

Rubber is oxidised more or less rapidly in the light. The free sulphur which the vulcanised rubber contains oxidises somewhat more rapidly still. The acid thus arising is a further agent in the destruction of the cotton.

Heat accelerates the oxidation of rubber in light and also the consequent attack of the (sulphuric) acid on the cotton. The action of heat on rubber proofings in the absence of light is not comparable with the action of light alone, and no judgment of the probable weathering behaviour of fabric can be based on it. Nor can the use of the mercury vapour ultra-violet lamp for artificial weathering satisfactorily replace actual exposure out of doors. Cotton is relatively more, and rubber much less attacked by the ultra-violet lamp than in the natural weathering test (Barr, *A.C.A., R. and M.* 313).

(i.) *Method of Protection.*—Dyes, both in cotton and rubber, and variously modified facings of rubber or dope on the outer cotton, have been used.

With one exception (an alizarin tried experimentally, see Barr, *A.C.A., R. and M.* 313) the dyes used have proved useless, or worse as far as the cotton is concerned. All, however, in some degree protected the rubber even where they did not aim at doing so, as in the use of green dyes for ground camouflage in kite balloons. Some dyes used in the rubber (*e.g.* Toluene-azo-toluene-azo-B Naphthol) specifically for its protection have proved very successful. Such dyed rubbers show no appreciable change in permeability or any marked oxidation as tested by acetone extract after months of exposure. They are dyes possessing a marked absorption in the ultra-violet. In spite of this they do not protect the cotton. This may be due to the fact that they do not prevent the oxidation of the free sulphur in the rubber.

The protective rubber coating that has proved most successful is one of 50 gm./m.^{2} containing some 20 per cent of litharge and 3 per cent of sulphur. It has a finishing coat of aluminium dust. This proofing is very black and opaque, said to be due to the presence of colloidal lead sulphide, though the actual amount of this substance is small, probably not 10 per cent of the lead being present in this form. It is, moreover, fugitive, being oxidised to lead sulphate. In spite of this it gives good protection. The aluminium finish is valuable as it reflects a good deal of the light, but at its best it is insufficient alone.

The gas-holding rubber lying between the cotton plies is also well protected in this way, showing little increase in acetone extract after months of exposure. The free sulphur, however, does slowly oxidise, and the acid thus formed presumably accounts for the slow loss in strength of the fabric. No examination seems to have been made of the nature of the light, if any, penetrating this type of protective coating.

The part played by tension in causing deterioration is very important, and its neglect has resulted in wrong conclusions being drawn as to the course which decay of a fabric will follow in service. When comparative weathering tests are made on pieces of fabric in tension and unloaded, it is found that the rubber in the tensioned pieces has failed far more than in the unloaded ones. In certain fabrics part of the cause of this is very easy to see. As a result of stretching, the outer protective rubber film roughens and the aluminium no longer lies as a smooth layer but is easily rubbed off. Briefly, tension makes the fabric more accessible to light. Probably, however, it acts in other ways too. Of three fabrics tested in this way one had a very opaque and permanent protective layer, the other two had relatively ineffective protection. In all three there was a marked difference between the permeability of the loaded and unloaded pieces, yet with regard to strength of fabric (which may be regarded as a rough measure of accessibility to light) the first was practically equal to its unloaded comparison piece while the other two loaded fabrics were weaker than the unloaded.

(ii.) *The General Course of Deterioration.*—If regard be paid only to exposure tests on unloaded samples, the conclusion may be reached (confining attention to reasonably good fabrics) that the rubber outlasts the textiles. Experience of fabrics in actual service points to the opposite conclusion.

In the decay of the rubber the early stages may be marked by a decided drop in permeability followed by a sudden large rise. A considerable and increasing acetone extract will be found for the rubber as these changes are encountered. Alternatively there may be a small rapid rise of permeability corresponding to the partial decay of the outer rubber, followed by a very slow rise as the rubber between the cottons is gradually attacked.

Broadly, what determines which of these two courses is followed is rapidity or slowness of attack.

If the protection is bad or the gas-holding rubber inherently unstable the former course is taken. Well-protected and relatively stable proofings follow the latter course.

Several cases are known, and as yet unexplained, where a very large increase in permeability, to four or five times the original value, occurs with no recognisable chemical change in the rubber.

It is clear that the attack on the cotton is from the outside. The actual seriousness of the loss of effective strength for a given percentage weakening of the outer ply depends on two things—(1) whether the outer ply is straight or biassed, (2) the mechanical nature of the more or less altered rubber. If the rubber has stiffened or has infiltrated between the yarns so as to glue them in position a much lowered tearing strength will result, and this effect will be enhanced if the outer ply is the one in direct tension. This may accompany a quite satisfactory tensile strength.

§ (5) Fabrics for Rigid Airships. (i.) *Outer Covers.*—These fabrics and the methods for their preservation are still in an experimental stage. Early attempts with linen or cotton either rubber or oil proofed were made. Acetate dopes similar to those used on aeroplanes but having much less contracting power were then tried. The conditions are, however, closely similar to those in an aeroplane wing, and the strength of the ship's structure is sufficient to allow ordinary aeroplane dopes to be employed. They are used in conjunction with the same opaque pigments and aluminium reflecting coat that have been found successful in protecting aeroplane wings. The most satisfactory textile appears to be a mercerised cotton.

(ii.) *Gas-bag Fabrics.*—As these are protected by the outer cover fabric, which stops all active light, the deterioration of the textile is negligible and the life of the bag is that of the impermeable skin lining. The principal deteriorating influences here are (1) changes in humidity, and particularly exposure to low humidity, and (2) heat.

For the skin to retain the mechanical support of the light cotton to which it is stuck, it must contract and expand with the textile and continue to adhere to it. Failure to do this does not necessarily entail porosity in the smooth unstressed fabric, but the result of creasing or tension when the skin has dried and contracted will be to rupture the skin. The skins as applied to the fabric are wet with a 5 per cent glycerine solution, the glycerine helping to maintain humidity, and therefore pliability, in the skin of the finished fabric. Attainment of the correct degree of tension in the skin at the time of laying it on the cotton is also of great importance.

J. W. W. D.

Bibliography

Very little published work is available. The statements made in the foregoing paragraphs are the broad results of experimental work carried on during the war and reported in confidential official papers. In some form or other some of this will probably become available through the publications of the new Aeronautics Research Committee.

In addition to the papers already cited, reference may be made to the following:

(1) *A.C.A., R. and M.* 584, particularly sections C and D.

(2) Articles in this Dictionary on "Aeroplane Wings, Doping of," "Aeroplane Wings, Fabrics for," "Diffusion of Gases through Membranes."

(3) *Aeronautical Journal*, July 1921.

Airship Fins, Efficiency of. See "Airships, Experiments on," § (21).

AIRSHIPS, AIRSCREWS FOR

(1) General.—The design of an airscrew for a given aircraft is governed primarily by the thrust required and the translational and rotational speeds at which it is to be developed.

It has been shown[1] that the conditions of working of an airscrew may be defined by the following undimensional factors:

$$\left(\frac{T}{\rho n^2 D^4}\right), \quad \left(\frac{Q}{\rho n^2 D^5}\right), \quad \text{and} \quad \left(\frac{V}{nD}\right),$$

where T is the thrust developed,
Q is the torque,
D is the diameter of the airscrew,
n is the number of revolutions per second,
V is the translational speed,
ρ is the density of the air,
η is the efficiency of working.

Moreover, the efficiency of working, which is $(VT/2\pi Qn)$, can be expressed as

$$\eta = \frac{T/\rho n^2 D^4}{2\pi Q/\rho n^2 D^5} \cdot \frac{V}{nD},$$

and is thus a function of these three factors.

It has been found that the resistance of an airship may be expressed as

$$R = C\rho l^2 V^2,$$

where l is the cube root of the displacement of the hull and C is a constant almost independent of V.

If there be m propellers each developing a thrust T, then

$$mT = C\rho l^2 V^2,$$

so that denoting $(T/\rho n^2 D^4)$ $(n^2 D^2/V^2)$ by K, we have

$$mD^2 = \frac{C}{K} l^2.$$

Hence, in order to obtain similar conditions of working (K constant) with similar airscrews, the total disc area of the airscrews is a function of C and l^2; that is, the disc area is determined by the form and size of the ship, and is independent of the speed V.

Further, with similar airscrews working under similar conditions, the efficiency η is constant, so that, since the horse-power varies as $(1/\eta)KV^3D^2$, the airscrew diameter needed to absorb a given horse-power increases with decrease of forward speed. Since the normal speed of an airship is in general less than that of an aeroplane, the above relation shows that an airship airscrew is larger in diameter than a similar one absorbing the same power at the same efficiency on an aeroplane. Also, since similarity of airscrews and equality of efficiency implies an equal value of V/nD in the two cases, and since V/D is smaller for the airship airscrew than for that of the aeroplane, n is smaller. It is therefore generally necessary to drive an airship airscrew through reduction gearing because its speed of rotation is much lower than the normal revolution speed of the engine. However, with the increased forward speed now being attained by airships the use of direct-driven propellers (in conjunction with engines designed to run at low speeds of revolution) is a probable development.

In this connection it is to be noted that fuel economy, and, therefore, airscrew efficiency, is of high importance for airships. A modern airship commences a normal flight with a weight of fuel of the order of 20 lbs. per horse-power installed. Consequently, an increase in airscrew efficiency of 5 per cent is equivalent to a saving of weight of the order of 1 lb. per horse-power.

§ (2) Variation of Airscrew Conditions with Translational Speed.—Modern rigid airships have from four to eight engines each driving one airscrew, and the speed is varied by running various numbers of engines at or near their full power. The loss of airscrew efficiency involved in so doing is much less than the loss of thermal efficiency which would result from reducing the speed of revolution of all the engines by throttling. (In the latter case, $(T/\rho V^2 D^2)$, and therefore the airscrew efficiency, remains practically unaltered.)

In practice, good efficiency is desired over a range of forward speed from full speed to about two-thirds of full speed. With a decrease of translational speed there is a small decrease of rotational speed of an airscrew driven by an engine whose torque is nearly constant, so that the corresponding variation of V/nD extends from its value at full speed to about 0·7 of this value.

§ (3) Variable Pitch Airscrews.—The use of the variable pitch airscrews on airships offers several advantages.

Airscrews of this type which have a sufficient range of angular blade movement provide a convenient means of obtaining the reverse thrust which an airship sometimes requires. In the case of an airship having ordinary constant pitch airscrews, some of these are fitted with a mechanical reverse gear in the transmission between engine and airscrew.

The airship may derive a further benefit from the ability to obtain reduced forward speed by increasing the pitch of the airscrews and allowing all the engines to run at reduced revolutions but at full torque, and consequently with good thermal efficiency.

By this method both the engine efficiency is maintained and the propeller efficiency is equal to or possibly better than that at full speed.

There is, however, a limiting speed—depending on the design of the airscrew—below which the efficiency of the airscrew falls

[1] See article "Airscrew, The."

off rapidly, when the pitch is increased in the above manner.

The airship has no requirement corresponding to the increased load when an aeroplane climbs, and to meet which the aeroplane decreases its pitch in order to maintain its revolutions and power. F. M. R.

AIRSHIPS, EXPERIMENTS ON

I. Resistance (Experiments on Full Scale)

§ (1) Measurement of Speed.—In experiments on airships a reliable method of measuring speed through the air is essential. An anemometer of the pressure type has been adopted where the head, in which the pressure difference is set up, is of the N.P.L. standard concentric pattern with true static tube. In order to avoid error due to proximity of the airship the head is lowered on a wire 50 feet long, to which are bound the rubber tubes connecting the head to the manometer in the car. Vanes are fitted on a rod extending to the rear, and the head is mounted in a stirrup between centres so as to be free to swivel in a vertical plane; the vanes also ensure alignment in a horizontal plane if care be taken not to twist the rubber tubes. A streamline weight of about 10 lbs., fitted with fins, is hung below the head to reduce horizontal deflection under the wind forces.

An alternative form for the head is that in which the pitot and static tubes are fixed in the streamline weight and project well forward of it; attached to the after end of the weight are four fins to ensure stable flight. The rubber connections are encased in flexible metallic tubing which is securely attached to the weight and serves as a support for the head. The latter form is convenient to handle and more robust, the fins being less liable to become distorted than those of the head first described.

The "flying" head is calibrated in the wind channel, the pressure difference in the two forms considered being equal to $\frac{1}{2}\rho V^2$ (where ρ is the density of the air and V the speed) when the correct flying attitude is obtained.

Owing to the comparatively low speeds of airships a sensitive manometer is required, and, since the inclination to the horizontal is continually varying, a type which is practically independent of the action of gravity is employed. If facilities for frequent calibration are available the Ogilvie indicator, 60-knot pattern, will be found most suitable of the standard types, for wind speeds up to 100 ft. per sec. A metal diaphragm instrument such as those made by Messrs. Munro will have the advantage of constant calibration, but the types available at the time of writing have lower sensitivity.

§ (2) Resistance.—Measurement of the resistance of an airship has been mainly attempted by two distinct methods, viz. by deceleration trials and by measurement of airscrew thrust.

The theory of the deceleration method may be stated as follows. At any instant when the thrust T is not equal to the resistance R we may write

$$T - R = M_e \cdot \frac{dV}{dt},$$

where dV/dt is the rate of change of speed and M_e the effective mass. The resistance at any speed in the accelerated motion under consideration may not be equal to the resistance at the same speed during steady motion, and it is customary to allow for this effect by the use of an "effective mass" derived from the true mass M by the use of a multiplying factor. While this method of correction is convenient and probably legitimate for any given body over the range where the resistance varies as the square of the speed, it may be noted that strictly the correction should take the form of a force per unit acceleration. For while there are many cases (a thin square plate in normal presentation is a good example) where the mass of the displaced fluid is negligible, there is little doubt that correction to the resistance of an airship for the effect of acceleration will be necessary.

The practical method of carrying out a deceleration trial is to run the airship at full speed, and, using an anemometer in which the damping is low, to observe the rate of change of speed when all power is cut off. Records may be taken by visual observation of the airspeed indicator and a stop-watch, or preferably by photographing both these instruments with a cinematograph camera. Plotting on a time base the reciprocals of the speeds thus obtained, the value of $dV/dt \times 1/V^2$ may be determined by measuring the slope; over the range where the resistance varies as the square of the speed the points should lie on a straight line.

Since the airscrew thrust is zero we may write

$$-\frac{R}{M_e} = \frac{dV}{dt} = S \times V^2,$$

where S represents $dV/dt \times 1/V^2$.

The true mass M of an airship in static equilibrium will be equal to the mass of the displaced air; but there is little reliable evidence as to the relation between M and M_e for the case of a body of streamline form in motion along its longitudinal axis. The correction is believed to be small, and at present there appears to be no alternative to the use of M in the place of M_e.

If ρ be the density of the atmosphere at the place of observation and l the cube root of the volume of the airship, the usual non-dimensional coefficient C will be equal to

$$-M\frac{dV}{dt}\times\frac{1}{V^2}\times\frac{1}{\rho l^2},$$

or, since M is equal to ρl^3 we may write

$$C=\frac{l}{S}.$$

It is found in practice that the results are represented by straight lines within fairly narrow limits, though local deviations, due presumably to gusts, are almost invariably present.

The second method of determining resistance by the measurement of airscrew thrust in steady motion eliminates the uncertain element of the acceleration correction, but the measurement of airscrew thrust has been found to be a matter of considerable difficulty.

At the time of writing, experiments are being carried out on an airship with a view to testing the method of Dr. Stanton and Miss Marshall,[1] in which the thrust is deduced from the increase in the total dynamic pressure of the air due to passing through the airscrew disc. The investigation has not yet progressed sufficiently far for an opinion to be given upon the accuracy of the method.

Valuable evidence as to the variation of the resistance with speed may be obtained by running all engines at a like speed and varying that speed over as wide a range as possible. Since the thrust varies as the square of the rotational speed N, and the resistance, for steady motion, is equal to the thrust, V/N is constant over the range where the resistance varies as the square of the forward speed V.

So far as observations have been taken on airships, the value of V/N has been found constant to the order of accuracy of the experiments.

§ (3) Local Speed Gradients.—Few observations have been made of the distribution of relative wind speed in the neighbourhood of the airship, but those which are available indicate that variations which occur in the measured speed are confined to a comparatively local region.

Measurements on airship R 33 indicate that beyond a point 30 feet below the car there was practically no change in the speed measured by the flying head; at 20 feet the local speed had a maximum value about 3 per cent higher than the forward speed of the airship. As the car is approached the rise in speed becomes more marked, and may amount to the order of 10 per cent at a few inches from the surface. The readings then fall sharply and the speed presumably becomes zero at the surface.

[1] *A.C.A., R. and M.* No. 475.

The increase of speed below the hull (at a point 55 feet aft of the nose) was found to be of the order of only 4 per cent near the surface. At the extreme after end of airship R 32, about 5 feet above the hull, the speed was about half that measured by a flying head at the forward end of the ship; but the ratio rose to about unity at a distance of 20 feet below the hull. Over a part of the intervening distance the speed was higher owing to the influence of the slip stream from the after airscrew.

§ (4) Distribution of Pressure over the Hull.—The pressures which act upon an airship still await experimental investigation, though a few preliminary observations indicated agreement with values obtained on models. In flight both the position, indicated by the configuration of the outer cover (whether pressed inwards or sucked outwards), for the change from pressure to suction at the head of the ship and also the presence of a pressure at the extreme tail are in agreement with the results obtained in a wind channel. The statement made above as to the pressure distribution is based on the assumption that the pressure in the interior of the hull is equal to the static pressure in the atmosphere, and the assumption is probably not seriously in error.

II. Resistance (Experiments on Models)

§ (5) Methods of Support.—One of the chief difficulties attending the measurement of the resistance of streamline bodies is the elimination of the effect of the supporting structure. It has been shown [2] that if the model be supported in the region of its centre of gravity on a rigid spindle of suitable stiffness, modification of the flow will take place. In the earlier experiments it was assumed that the resistance of such a spindle could be determined by the addition of a second similar spindle which would increase the total resistance by an amount equal to that due to the first spindle. Later experience has shown that this is not the case when the spindle causes a relatively large increase in the resistance. However, it has been found possible by the methods outlined below to make a satisfactory determination of the true resistance of the model, and therefore the effect of the first spindle may be assessed. Under these circumstances the use of a spindle rigidly supporting a model may be permitted in certain experiments.

To minimise the difficulty with the spindle in experiments of this nature, where the axis of the model is parallel to the wind direction,

[2] *A.C.A., R. and M.* 244 (Pannell and Campbell). A.C.A. = Advisory Committee for Aeronautics. R. and M. = Reports and Memoranda.

the dimensions of the supports are reduced to a minimum by suspending the model on steel wires of high tensile strength; the wind force on the model is transmitted to the balance by means of a projection in the tail which presses against a streamline spindle on the balance. With a model of an airship hull 4 feet long and 6 or 8 inches in diameter, supported on two wires 0·01 in. in diameter, the disturbance of the flow due to the wires is small, and the resistance of the wires and spindle may be accurately determined.

§ (6) Static Pressure Correction.—In a wind channel the air is accelerated as it passes along the whole length of the channel, and it has been found [1] that this acceleration is accompanied by a fall of pressure approximately proportional to the change in the square of the speed. In the measurement of the resistance of such a body as a right cylinder with its axis parallel to the wind direction, the static pressure at the up-stream face will be higher than at the down-stream face. Under the circumstances there will be measured on the balance, together with the resistance proper, an additional force equal to the difference of pressure between the two ends of the cylinder multiplied by the cross-sectional area. In the open air this force would not exist.

In the case of a streamline body this spurious force is equal to $\int P d A$, P denoting the pressure at a point where the cross-sectional area is A.

§ (7) The Effect of Form on Resistance.—An inquiry has been carried out at the National Physical Laboratory on the resistance of a series of 78 different forms; [2] the models, with the exception of seven instances, were built up by the use of separate wooden pieces constituting the head, tail, and central cylindrical portion. The lengths of the models varied from 28 in. to 53 in., the diameter was 6 in. throughout, and the speed ranged from 25 to 80 ft. per sec. The models had a varnished surface, and local irregularities caused by slight variations in the diameters of adjacent sections were faired with plasticene.

Limitations of space preclude the possibility of a detailed examination of these results, but the broad conclusions may be stated as follows:

1. A tail 2·5 diameters long can be made to give as low a resistance coefficient as any other tail yet examined.

2. A form 4·6 diameters long can be produced which will give a resistance coefficient of 0·007. The forward curved portion of such a body may be elliptical and must be at least 2 diameters long. There should be no cylindrical portion.

[1] *A.C.A., R. and M.* 564 (Pannell, Jones, and Pell).
[2] *A.C.A., R. and M.* 607 (Pannell and Jones).

The resistance coefficient of the envelope of a Sea Scout "S.S." non-rigid ship, 5·2 diameter, is 0·013; that of the hull of the rigid airship L 33 is 0·011.

3. For all the models examined, except in a few isolated cases, the introduction of cylindrical body causes an increase in resistance coefficient at the higher speeds.

4. In forms which include a cylindrical body more than one diameter in length, a tail composed of a series of truncated cones and 2·75 diameters long may be used without appreciable increase in the resistance coefficient at the higher speeds.

§ (8) The Resistance of Component Parts.—The resistance of the fins, cars, etc., of an airship have been determined in the wind channel for two types of airships only, viz. the R 23 [3] and R 33 [4] types. It is considered inadvisable to test a fully-rigged model in the wind channel, mainly because, owing to the small scale, many of the parts of small dimensions would be subject to considerable "scale effect."

The method adopted in the experiments referred to was to test the hull and fins to scales of 1/133 and 1/120 respectively; a preliminary experiment indicated that the interference between the cars and the hull is probably negligible on full scale, and the former were therefore tested on larger scales in the absence of the hull. The resistance of the wires was calculated from the results of previous experiments in a wind channel,[5] and the resistance of the radiators was estimated from tests of full-size radiators constructed of tubes similar to those of R 26 [6] and R 33 respectively.

This inquiry showed that the total resistance was composed, as to the principal items, as follows:

Part of Ship.	Percentage Resistance. R 23.	R 33.
Hull with fins	68	69
Cars	20	14
Wires	5·8	7
Radiators and supports	4·5	6·1
Various	1·7	3·9
Total predicted coefficient, $R/\rho V^2 l^2$	0·030	0·0197
Coefficient observed in deceleration trials	0 025	0 0173
Ratio of coefficients	1·20	1·14

An examination of the results for the model hulls shows that the coefficient falls rapidly in the case of R 23 at the highest speed attainable in the wind channel, and the excess of the value for the model over that for the ship is no doubt to some extent due to this cause. In the case of R 33 the change in the coefficient is much less marked. Assuming that M_e is about 1·15M (see § (2)), and this is probably a good estimate, the agreement between the observed and predicted results is good.

[3] *A.C.A., R. and M.* 619 (Pannell, Jones, and Pell).
[4] *A.R.C., R. and M.* 827 (Frazer and Gadd).
A.R.C. = Aeronautical Research Committee.
[5] *A.C.A.*, 1913–14, p. 47.
[6] *A.C.A., R. and M.* 273, and *R. and M.* 221.

III. Stability and Control (Experiments on Full Scale)

§ (9) Determination of Turning Circle.—The conditions which prevail during steady turning motion of an airship may be examined

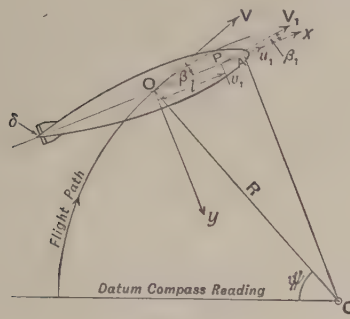


Fig. 1.

by reference to *Fig.* 1, and the following system of symbols has been adopted:

O, the origin of co-ordinates coinciding with the C.B. (centre of buoyancy) or the centre of volume of the hull.[1]

O*x*, the axis along the centre line of the hull; positive direction forward.

O*y*, the axis perpendicular to the plane of symmetry; positive direction to starboard, *i.e.* to the right.

O*z*, the axis perpendicular to *xoy*; positive direction downwards.

V, the speed along the flight path at the centre of gravity G of the airship.

V_1, the speed measured at position P.

β, the true angle of yaw (*i.e.* the inclination of *ox* to the flight path at the C.G. of the airship).

β_1, the local angle of yaw at point P.

u_1, component of V_1 along *ox*.

v_1, component of V_1 along *oy*.

G, position of the centre of gravity.

P, position at which the anemometer, yawmeter, and compass are located.

d, the distance between the points G and P.

A, position at which there is no side-slipping.

R, radius of the turning circle.

ψ, compass reading at any time.

Longitudinal component

$$u_1 = V_1 \cos\beta_1 = V \cos\beta. \quad . \quad . \quad (1)$$

Lateral component

$$-v_1 = V_1 \sin\beta_1 = V \sin\beta - \dot{\psi}d, \quad . \quad (2)$$

$$\therefore \tan\beta_1 = \frac{V\sin\beta - \dot{\psi}d}{V\cos\beta} = \tan\beta - \frac{\dot{\psi}d}{V_1\cos\beta_1}, \quad (3)$$

or

$$\tan\beta = \tan\beta_1 + \frac{d\dot{\psi}}{V_1\cos\beta_1}. \quad . \quad . \quad (4)$$

Equation (4) therefore determines the true angle of yaw β in terms of the measured quantities β_1, $\dot{\psi}$, and V_1.

The radius of the turning circle is clearly given by $V/\dot{\psi}$, whilst the component of the centrifugal force normal to the ship's axis must balance the lateral force Y. These results may be expressed by the use of two further equations,

$$R = \frac{V}{\dot{\psi}}, \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and

$$Y = \frac{MV^2}{R}\cos\beta. \quad . \quad . \quad . \quad (6)$$

Since in practice β rarely exceeds 7 degrees, V in equations (5) and (6) may be replaced by the measured speed V_1 with an error not exceeding 1 per cent.

Equation (5) now determines the radius of the turning circle, a quantity which, for convenience in comparing different airships, is usually doubled and divided by the length of the airship. This non-dimensional quantity has been termed the turning coefficient.

§ (10) The Measurement of Angle of Yaw.—In the conduct of turning trials on airships, the speed V_1 is measured by a flying head lowered from the forward car, $\dot{\psi}$ is determined from readings of the compass or a sundial plotted against time, and β_1 from readings on a yawmeter. In the yawmeter employed on the earlier trials a yaw head similar to those described in *A.C.A., R. and M.* 445 is fitted on the end of a mast of streamline section, which projects below the forward car. Briefly, the yaw head consists of two open-ended tubes set in the form of a "V"; for high sensitivity the tubes include an angle of about 120°. In measuring the angle of yaw the mast is rotated about its axis until there is equality of pressure in the two tubes; the angle of yaw is given by the rotation from the zero position necessary to secure equality of pressure in the tubes during straight flight. Such an instrument gives a reading of angle of yaw without calibration, and is usually satisfactory under steady conditions.

In flight, however, there is found to be invariably a certain amount of disturbance even on days when the atmospheric conditions appear to be almost perfect, and for this reason apparatus which requires adjustment

[1] The present consideration of equilibrium and stability relates to lateral motion, and for convenience a system of axes has been adopted which differs from the standard system (see "Aircraft, The Stability of"), in that the origin is situated at the C.B. instead of at the C.G. The C.G. is assumed to be on the axis *oz*.

before a reading can be taken is unsatisfactory. There are several alternative methods, and experiments are in progress with a view to producing an instrument in which no adjustment is required before a reading can be taken.

§ (11) CONTROLLABILITY.—The power of the captain of an airship to control the vessel will be employed under two main conditions of flight, in which the requirements are to some extent diametrically opposed. In one case during manœuvres the airship will be required to turn quickly under the action of the control surfaces, and in the other case on long flights ability to maintain any given course indicates a high degree of controllability, under these particular conditions. For on many airships, in spite of constant adjustments of the control surfaces, there will be appreciable departure from straight flight, and to that extent the airship must be regarded as uncontrollable.

Controllability in this second sense is essentially a question of stability, and a stable ship were obtained in this manner for the stable airship R 29,[1] and the unstable ship R 33.

The method of observation adopted was to record the compass readings against time while moving the rudders at known intervals over a small range of angle on either side of amidships. The results obtained are given in *Fig.* 2. The experiment on R 29 may be regarded as commencing at time five minutes, and it will be noted that though observation was continued for 22 minutes the rudder angle was only changed twice, the deviation from the mean course amounting to less than 20°. On R 33 the rudder angle was changed eleven times in the same period, and it was only by keeping the closest watch that the variations from the course shown in the figure were not exceeded.

The variation of course for R 33 was about 35° on either side of the mean, that of R 29 only 18°. The path of R 33 would of course have been more nearly straight had larger rudder angles been employed ; but it would be

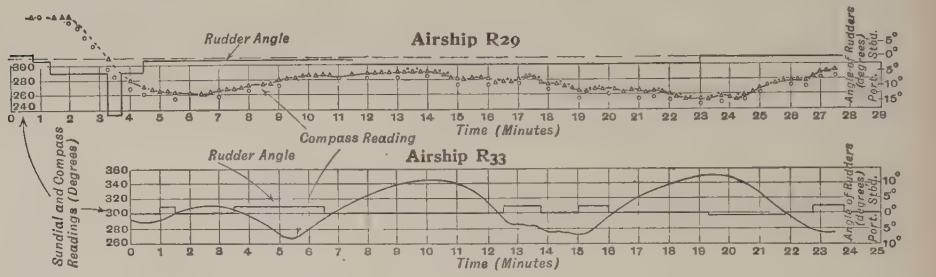


FIG. 2.

may be readily flown on a given course in calm weather. Under disturbed atmospheric conditions, however, as a consequence of the large surfaces necessary to render an airship stable in calm weather, large forces are brought into operation at the tail, due to gusts, and the controllability becomes very low. For this reason, and to secure facility of manœuvre, modern airships are likely to be uniformly unstable.

It should be noted that the use of a large part of the stabilising surface for control purposes (as in Italian airships) will be advantageous if the constructional difficulties can be overcome. Alternatively, the required improvement may be secured by the use of more efficient control surfaces (see § (21)).

The exact measure of controllability is a matter of considerable difficulty, since in ordinary navigation the behaviour of the airship will depend largely upon the skill with which the control surfaces are manipulated. This source of error is to some extent eliminated if the controls be operated throughout a series of observations by the same person, and it may be of interest to give some results which practically impossible to secure rectilinear flight with the same accuracy as on R 29, and the method adopted appeared to be more suitable for making a comparison with other airships possessing a higher degree of stability.

§ (12) REVERSAL OF CONTROL.—While dealing with controllability it will be appropriate to consider a certain anomalous condition which frequently arises in flight. In the normal functioning of the elevators it would be expected that the rear end of the control surface would be depressed (resulting in an upward force) when it was desired to fly the airship pitched nose down. In practice the reverse is frequently the case, it being often necessary to raise the elevators when flying nose down, in order to prevent the airship taking up a larger angle to the horizontal than is desired.

These conditions arise when the aerodynamic disturbing moment, with elevators horizontal, exceeds the static restoring moment, and the effect on an unstable ship such as R 33 is naturally much more marked than on R 29.

§ (13) DYNAMIC LIFT.—In navigating an airship much use is made of the vertical

[1] *A.R.C., R. and M.* 675.

component of the force which acts when the axis of the ship is inclined in the vertical plane to the direction of motion. In such a position the air forces on the ship have a vertical component. A rigid airship is subject to considerable departures from static equilibrium, the airship becoming either light, due to superheating of the gas, or heavy, due to rain or snow, and the dynamic force on the hull and stabilising surfaces is used to counteract the unbalanced static force.

This method of maintaining equilibrium has the serious disadvantage that an appreciable loss of speed is incurred owing to increase of resistance when the hull is inclined more than a few degrees. The loss of speed may amount to as much as 20 per cent for an angle of pitch of 10°, and this angle is by no means uncommon in normal navigation. The use of elevator angles of high magnitude will also result in loss of speed.

The phenomenon of reversal of control, discussed in § (12), may have unpleasant consequences when it is necessary to make use of considerable dynamic force by flying at a large angle of pitch. Imagine an airship flying on a horizontal path at a certain speed, pitched nose down at 10°, and with the elevators inclined upwards at the maximum angle. The static righting moment will, under these conditions, be balanced by an aerodynamic disturbing moment which has been reduced to a minimum by deflecting the controls through the maximum angle; the vertical dynamic force on the hull will be equal and opposite to the excess lift of the airship.

If now the speed be increased and the aerodynamic disturbing moment acting on the ship is assumed unchanged, loss of height will at once occur owing to the increased downward dynamic force. No reduction of the angle of pitch can be effected since the elevators are already inclined at the maximum angle, and as a consequence the airship is unable to fly above a certain speed. Actually the magnitude of the effect is increased owing to the aerodynamic disturbing moment becoming greater at the higher speed. If it be possible to release gas, normal navigational conditions are again restored, since a smaller angle of pitch is required to produce the necessary downward dynamic force, and effective control by the elevators is again secured.

The return of R 34 to her base after the accident of January 1921 was delayed through this cause, and it is possible that her total loss would have been avoided had she been able to proceed continuously at full speed. There is little doubt that the solution of this problem of the control of altitude would have a far-reaching effect on the navigation of rigid airships.

§ (14) Pressure on the Stabilising Surfaces.—At the time of writing little information is available as to the pressures which act in flight on the fins and control surfaces of airships. Experiments are, however, in progress on airship R 32, to determine the forces active on the upper vertical fin and rudder, and from the preliminary results a few conclusions of a general character may be drawn.

When the ship is turning, the regions of high pressure are situated towards the forward end of both fin and rudder. This result was anticipated, as a similar distribution of pressure had been observed in wind-channel experiments on inclined surfaces. The observations for the leeward side show a reduction of pressure below the static, of greater magnitude than the increase of pressure on the windward side. For convenience the results are expressed in the form of non-dimensional coefficients ($P/\rho V^2$), the pressures on the two sides of the fin being subtracted algebraically at each observation-point.

During the turning trials with the rudder hard over, the higher coefficients were of the order unity (corresponding to 15 lbs.-ft.^{2} at 80 ft.-sec.) at speeds above 70 ft.-sec. At the lower speed the coefficients were higher, but it is difficult to decide whether the change is due to scale effect, or to the greater effect of gusts when the forward speed of the airship is low.

§ (15) Stability.—The determination of the stability of an airship in flight is a matter of considerable difficulty. In the recent trials of airships an attempt has been made to determine the relative lateral stability of different ships by observation of the flight path when the rudders are locked at or near amidships.

It appears that it should be possible to find, for any stable airship, a position for the rudders which would result in the mean course being straight, whereas for an unstable ship with the control surfaces amidships, the flight path would become increasingly curved until a condition of stable equilibrium was reached.

Observations of this nature therefore afford a means of determining if a ship is stable, and, if not, the curvature of the path expressed in terms of the length of the airship, may indicate the degree of instability, though the problem in the latter case may be complicated by the effect of speed. The results obtained on airship R 33 appeared to indicate a decrease of instability as the speed increased; but the observations were very incomplete and the result awaits confirmation.

IV. Stability and Control (Experiments on Models)

§ (16) Introductory.—In addition to a knowledge of the resistance coefficient of an airship, information is generally required concerning the aerodynamic characteristics of the airship envelope and stabilising surfaces, when the axis is inclined to the wind.

The more important characteristics which

come under consideration when considering equilibrium, stability, and controllability are (i.) the lateral force, *i.e.* the force acting along the y axis; (ii.) the normal force, *i.e.* the force acting along the z axis; and (iii.) the aerodynamic couples about the axes of z and y, *i.e.* the yawing and pitching moments.

It is assumed that if the airship be turning the aerodynamic forces and couples may be resolved into two parts, the one due to translation and the other due to rotation.

It is usual to suppose the components due to translation to vary as the square of the velocity of the C.G. relative to the air. This is probably not strictly true, the evidence available indicating that the forces increase rather more rapidly than the square of the speed, the reverse being the case with the couples.

Further, the component due to rotation is assumed to vary directly as both the rotational velocity and the translational velocity, so that, for example, when an airship is flying in a curvilinear path with angular velocity r, the component of the yawing moment N due to rotation is $r(\partial N/\partial r)$ or rN_r, N_r being proportional to the forward velocity V. If the yawing moment due to side-slipping at an angle of yaw β be denoted by N_β, the total couple on the airship is $N_\beta + rN_r$.

§ (17) Measurements of Forces and Moments due to Translation.—The motion obtaining in a wind-channel represents a purely translational motion of the airship model at various angles of presentation to the wind. The quantities that are directly measured are:

(i.) Drag, lift, and pitching moments, at different angles of pitch.

(ii.) Drag and cross-wind force and yawing moments at different angles of yaw.

Drag, lift, and cross-wind force are the forces along axes parallel, and perpendicular, to the direction of the relative wind.

A very brief sketch of the manner in which these quantities are measured must suffice; for a more detailed description of the apparatus see "Model Experiments in Aeronautics, III."

For these experiments the model is mounted rigidly on a vertical spindle which is firmly held in the main aerodynamic balance. Variations in the angle of presentation are secured by rotating the upper part of the balance about a vertical axis. For measurements at angles of pitch the model is mounted with the plane of symmetry horizontal, *i.e.* on its side.

This method gives directly the drag, lift, and pitching moments on the model, the first two quantities are readily converted into components acting along, and perpendicular to, the axis of the model (*i.e.* along the axes of x and z), in which form they are applied to stability investigations.

Similarly, by mounting the model in its normal attitude with the plane of symmetry vertical, the values of the longitudinal and lateral forces, and yawing moments at different angles of yaw, are determined.

In view of the fact that an airship envelope is approximately a solid of revolution with the horizontal and vertical fins not very dissimilar, the variation of the normal force and pitching moment with angle of pitch is similar to that of the lateral force and yawing moment with angle of yaw. Hence, to avoid repetition motion in yaw only need be considered, it being understood that, in general, the remarks made concerning lateral force and yawing moments apply to normal force and pitching moments.

The lateral force and yawing moments are usually measured at angles of yaw varying from 0° to 20° under the following conditions:

(i.) Hull only.

(ii.) Hull and cars.

(iii.) Hull, cars and fins, with rudders amidships.

(iv.) Hull, cars, and fins, with rudders inclined.

The difference between the first two sets of observations gives the effect of the cars, and between the second and third the effect of the fins. A measure of the fin efficiency is obtained on reducing the lateral force and yawing moment due to the fin to the form of coefficients by dividing the one by ρV^2 times the area of the fins, and the other by the product of ρV^2, the fin area and the distance of the centre of area of the fins from the C.G.

Similarly, from (iii.) and (iv.) the force and moment due to inclining the rudders are obtained; these quantities furnish a measure of the rudder efficiency when reduced, as above, to the form of coefficients and further divided by the angle of inclination of the rudders to the fixed fins.

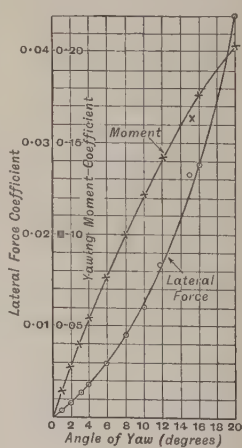


Fig. 3.

§ (18) Forces and Moments on the Hull, due to Translation.—In *Fig.* 3 typical curves are given showing how the lateral force and yawing moment on the hull alone vary with the angle of yaw. One curve represents the lateral force $\div \rho AV^2$, where A is the area of the longitudinal section of the hull, *i.e.* the area

of the section of the hull by the plane of symmetry of the ship. The other curve gives the yawing moment $\div \rho V^2 l^3$ K, where l^3 is the volume of the hull, and K the ratio of that part of the area A forward of the axis Oz to that at the rear of it. These quotients have been found to be approximately constant for a large number of differently shaped envelopes, and a mean value is plotted in the curve. It is to be understood that the moment is a disturbing moment, the envelope being unstable as a weathercock.

§ (19) Effect of Cars.—The addition of the cars naturally increases the lateral force [1]; but, with the cars distributed approximately uniformly along the hull, the moment remains practically unchanged. The increase in the lateral force due to the addition of these cars amounts to 70 per cent at small angles of yaw on R 29, about 32 per cent on R 32, and 20 per cent on R 38; at 20° angle of yaw these magnitudes are 40, 22, and 10 per cent respectively in the three cases. From a stability point of view the higher lateral force is desirable, but it is accompanied by an increase in resistance. The longitudinal forces corresponding to the above increases in lateral force are greater by 20, 35, and 35 per cent at small angles of yaw.

§ (20) Fin Efficiency, Rudders Amidships.—In *Fig.* 4 is given a mean curve obtained from a number of experiments on various models showing the lateral force coefficient on the fin, *i.e.* the lateral force $\div (\rho V^2 \times$ fin area). An exactly similar curve is obtained for the moment coefficient per unit distance (λ) of the C.G. from the centre of area of the fins. The sign of the moment is, however, different from that of the force, and its magnitude is 10 per cent less.

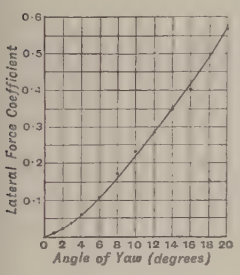


Fig. 4.

Thus, if instead of dividing the actual moment due to fins by λ, a length $\lambda_1 = 0{\cdot}91\ \lambda$ had been used, the magnitude of the force and moment coefficients would have been equal, showing that the centre of pressure of the force on the fin is forward of the centre of area, and by a distance equal to about 10 per cent of the distance between the centre of area and the C.G.

The sign of the force is the same as that on the hull only, there being an increase in the lateral force due to the addition of the fins with rudders amidships. The sign of the two moments being different, the moment on the hull with fins is less than that on the bare hull. The fin area usually fitted to rigid airships is not, however, sufficient to make the ship stable as a weathercock in translational motion at angles of incidence of the magnitudes encountered in actual flight.

The force on any particular fin probably depends in some definite manner on the form of the fin and also on the form of the hull, but the evidence available (March 1922) is not sufficient for any satisfactory law of variation to be deduced. The curves given are, however, such as a designer could use to determine the approximate fin area necessary to give a certain force or moment on a particular ship, the quantities due to the hull having been determined from the curves given in *Fig.* 3.

§ (21) Efficiency of the Control Surfaces.—A method of comparing the efficiency of different types of airship rudders has been mentioned above. It is found that the ratio of the moment due to inclining the rudders to the corresponding force is, as in the case of fins, approximately equal to the distance of the rudder hinge from the C.G. of the ship; as the controllability of an airship in lateral motion depends on the variation, with rudder setting, of the moment due to rudder, attention may be confined to a consideration of the moment coefficient as defined in § (17). Three types of rudders will be compared.

(*a*) Rudders of the type fitted on R 33, and in fact on all rigid airships built in Britain prior to R 38. In this type the axis about which the rudder turns is placed aft of the leading edge by about $\frac{1}{4}$ of the width of the rudder, and the balancing area extends along the whole length of the rudder, so that when the latter is inclined there is a gap between it and the fin.

(*b*) Rudders of the type fitted on R 38. In this case the balancing area is concentrated at the edge of the rudder away from the hull for about $\frac{1}{3}$ the length of the rudder, the rudder axis being coincident with the leading edge for the remaining $\frac{2}{3}$ of its length. There is no gap between fin and rudder except at the balancing area.

(*c*) Unbalanced rudders, with the axis coincident with the leading edge of the rudder along its whole length, and no gap between fin and rudder. The force necessary to operate unbalanced rudders of this type renders them unsuitable for use on rigid airships.

The relative efficiencies of these three types fitted on a model of the R 33 hull are as follows: Type (*c*) 1·00, type (*b*) 0·89, and type (*a*) 0·66, showing that, from the point of view of obtaining maximum control, type (*c*) is the most efficient. This is probably due to the discontinuity of the surface being less pronounced when the rudders are inclined.

It may be noted that removing the fabric

[1] This does not apply to normal force

from the upper fixed fin, while retaining the rudder, decreased the efficiency of the rudder system of R 29 by 30 per cent.

Regarding the rate of change of the moment due to rudders with inclination of rudders, it may be stated, generally, that this rate of change is greatest at zero inclination, and does not decrease appreciably till an angle of about 20° is reached, after which, in the case of type (*a*), it decreases rapidly at higher angles, and is zero at about 25° or 30°.

A curve showing the moment coefficient due to rudders of type (*a*) is given in *Fig.* 5.

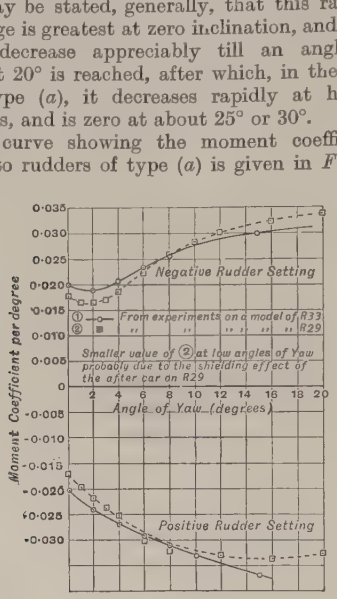


FIG. 5.

The moment is negative when the rudder setting is positive, and *vice versa*.

In connection with rudders of types (*b*) and (*c*) information is available regarding hinge moments, *i.e.* the couple about the rudder axis at different angles of its inclination. In the cases considered the ratios of the areas forward of the hinge to that aft are for type (*b*) 0·141, 0·212, and 0·283; the corresponding ratio is obviously zero in type (*c*). When the ratio was 0·283 the hinge moment was practically negligible for angles between $+10°$ and $-10°$, showing that the rudder was approximately balanced. As it is, however, desirable to have an airship rudder under- rather than over-balanced, the balancing area is probably excessive. In the three other cases the hinge moments on one rudder calculated from models for an actual airship at zero yaw and 10° rudder angle are 308 and 184 lbs.-ft. (ratios of areas 0·141 and 0·212) and 596 lbs.-ft. (ratio 0) when flying at 60 ft./sec. or 41 m.p.h. The total areas of the rudders are 227, 241, and 198 sq. ft. respectively.

It is now possible to calculate the lateral force or yawing moment due to translation on a model whose dimensions are given, at different angles of presentation to the wind, and with rudders set at various angles within the range generally found in practice.

§ (22) LATERAL FORCE AND YAWING MOMENT DUE TO ROTATION.—As has been indicated, the aerodynamic lateral force and moment due to turning are mrY_r and rN_r, where m is the mass of the airship, r the angular velocity, Y the aerodynamic lateral force per unit mass, and N the total yawing moment. There is, of course, a centrifugal force acting, but this need not at present be considered.

No description of a direct experimental method for obtaining the value of Y_r has yet been published in England, and an accurate determination of the total lateral force, and hence the positions of equilibrium of an airship in curvilinear flight, is apparently very difficult.

A method of calculating this derivative, using the results of experiments both on a model and on the full-scale airship, will be given below. The results show that Y_r may vary from about 0·4V to 0·75V on a ship with different fin areas, Y_r on the bare envelope being about 0·1V, where V is the forward speed of the ship. Further, the variation of Y_r with angle of yaw is probably small.

With regard to N_r a description of the methods used and the principles involved in determining it in the wind-channel is given in detail under "Model Experiments in Aeronautics." Experimental results indicate that on a complete model of an airship the fins are responsible for by far the greater part of N_r as well as Y_r. For example, on a model of R 29 with three different sets of fins of area 0·0932, 0·0822, and 0·0690 sq. ft. the values of N_r/V are $1·51 \times 10^{-3}$, $1·49 \times 10^{-3}$, and $1·23 \times 10^{-3}$, whereas on the hull only N_r/V is $0·35 \times 10^{-3}$.

Moreover, if the value of N_r/V due to fins be reduced by dividing by the area of the fins and $\lambda_1{}^2$,[1] the coefficients obtained are $4·36 \times 10^{-3}$, $4·64 \times 10^{-3}$, and $4·23 \times 10^{-3}$. Corresponding coefficients on other models lie in the neighbourhood of $4·3 \times 10^{-3}$, the mean value comparable with the mean values discussed above being $4·3 \times 10^{-3}$.

Mention may be made of a manner in which Y_r/V due to fins may be approximately estimated. It has been found in four cases considered that N_r/Y_r due to fins at zero yaw is approximately equal to the ratio of $\partial N_\beta/\partial\beta$ to $\partial Y_\beta/\partial\beta$ when $\beta=0$, and a good first approximation to Y_r/V on the complete ship may be derived by increasing the value of Y_r/V due to fins so obtained by 0·1.

Finally, reference may be made to a method used in Italy to determine the total lateral force and yawing moment on an airship model

[1] λ_1 = the distance between the C.G. of the airship and the C.P. of the forces on the fins.

moving in a circle. The model is mounted on a whirling arm, and the fluid medium in which the model moves is water. The values of Y_r and N_r are obtained by taking the slope of the curves in which lateral force and yawing moment are plotted against r. Calculated in this manner for an Italian non-rigid airship, type M, Y_r was found to be of the order 0·6 V.

§ (23) The Determination of the Equilibrium Attitudes of an Airship in Curvilinear Flight for various Rudder Settings.—It now remains to consider the application of the results of experiments on models to determine the angle of yaw and the radius of the circle in which the C.G. of an airship moves, for any particular rudder setting.

At the outset the assumption is made that these quantities are independent of the speed, since the evidence of speed effect on the lateral force and yawing moment is insufficient to justify the application of a systematic correction.

There are two conditions to be satisfied:

(*a*) The total yawing moment about the axis of z must vanish, *i.e.*

$$N_\beta + rN_r = 0, \quad . \quad . \quad . \quad (1)$$

where N_β is the yawing moment due to translation when the angle of yaw is β.

(*b*) The total lateral force must be equal and opposite to the component of the centrifugal force along the y axis, *i.e.*

$$mY_\beta + mrY_r = m\frac{V^2}{R}\cos\beta = mu_0 r, \quad . \quad (2)$$

m being the mass of the airship, mY_β the lateral force due to translation at an angle of yaw β, and u_0 the component of V along the axis of x in steady flight.

It has been assumed that the forces and moments due to translation vary as the square of the speed, whence it follows that the resistance derivatives vary as the speed. Further, as the values of β hitherto encountered on rigid airships are not greater than about 7°, no appreciable error will be introduced by putting $u_0 = V$, so that at unit speed equations (1) and (2) may be written

$$N_\beta' + \frac{1}{R}.N_r' = 0, \quad . \quad . \quad . \quad (3)$$

and

$$Y_\beta' + \frac{1}{R}(Y_r' - 1) = 0, \quad . \quad . \quad . \quad (4)$$

where

$$N_\beta',\ Y_\beta' = \frac{N_\beta,\ Y_\beta}{V^2},$$

and

$$N_r',\ Y_r' = \frac{N_r,\ Y_r}{V}.$$

Since, however, no direct experimental method has been developed to determine Y_r' it is impossible to deduce from these two equations the values of β and R. If Y_r' were known the calculation would be simple graphically, for, writing equations 3 and 4 in the form

$$-\frac{1}{R} = \frac{N_\beta'}{N_r'} = N, \quad \text{and} \quad -\frac{1}{R} = \frac{Y_\beta'}{Y_r' - 1} = Y,$$

and plotting N and Y against β for any particular rudder setting, the intersection of the two curves would give immediately the required value of R and β. Supposing, however, that β were known, then from the curves N against β, R is found immediately, or *vice versa*. An application of these values of β to the curves Y_β against β will give $(Y_r' - 1)/R$, whence having determined R the value of Y_r' is available.

Examples are given in *Fig.* 6 in which use has been made of observations of β obtained on flights in Airship R 29, fitted with three different sets of fins.[1] The values of R calculated as above agree to within 5 per cent with the actual observed values.

An interesting characteristic of airship motion is evident from the figures. It is seen that the curve through the points indicating the position of equilibrium is nearly a straight line through the origin, and thus $R\beta = \text{constant} = K$; R sin β is also constant since β is small.

This constant is approximately the same for the three cases, hence it appears to depend on hull characteristics only. If reduced to a non-dimensional coefficient by dividing by the distance of the C.P. of the forces on the fins from the C.G. (λ_1), it has been found to be nearly constant for R 29, R 32, and R 33.

The physical significance of R sin $\beta = K$ is interesting. First, if v_0 be the component of V along the axis of y in steady flight, then $v_0 = -V \sin\beta$, and since $rR = V$, $v_0/r = \text{constant}$, or the ratio of side-slipping velocity to the angular velocity is constant in a steady turn.

Secondly, the foot of the perpendicular from the centre of the turning circle to the axis of the ship is a constant distance from the C.B. Also, the axis of the ship will at the point always be tangential to a circle concentric with the turning circle, so that the value of K defines a point at which the side-slipping velocity is zero.

Thirdly, the distance of this point from the C.G. bears a constant ratio to λ_1 from ship to ship.

§ (24) Stability in Rectilinear Flight.—Suppose the total moment $N' + N_r'/R$ at unit speed plotted against β, by symmetry, this moment is, of course, zero when $\beta = 0$. If the airship originally flying straight ahead with $\beta = 0$ were given a small displacement β positive, then if the moment be positive at this small positive value of β, the airship tends to depart further from the position of equilibrium $\beta = 0$, and equilibrium at $\beta = 0$ would

[1] See *A.R.C., R. and M.* 675.

be unstable. The reverse would obviously be the case if $N'_\beta + N'_r/R$ were negative at the small positive value β.

The condition of stability can then be written

$$\frac{\partial}{\partial\beta}\left(N_\beta' + \frac{1}{R}N_r'\right) < 0,$$

or since

$$\frac{1}{R} = \frac{\beta}{K},$$

$$\frac{\partial}{\partial\beta}N_\beta' + \frac{N_r'}{K} < 0 \text{ at } \beta = 0.$$

other hand, $|N_r'| < K|N_v'|$ the two curves intersect at two other points, representing two equal and opposite values of β which define the attitude an airship unstable in rectilinear flight would take up in order to fly with its rudders amidships; under these conditions the C.G. would no longer move in a straight line. The positive value corresponds with a turn to starboard and the negative with a turn to port.

Similar considerations apply to lateral force.

With regard to the equilibrium positions with rudders inclined at the angles for which curves are given in *Fig.* 6, the slopes of the curves are always such as to give stability.

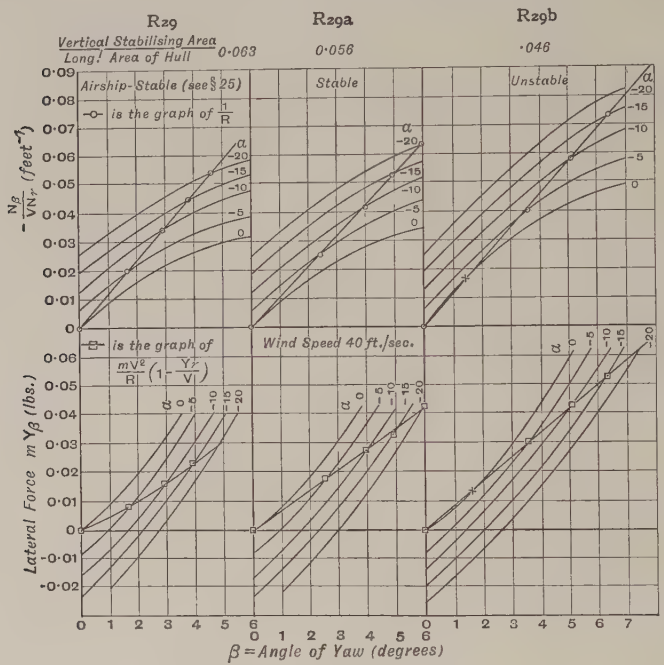


FIG. 6.

But $\partial N_\beta'/\partial\beta = -N_v'$ where N_v is one of the usual resistance derivatives, and hence the stability condition becomes

$$\frac{N_r'}{K} < N_v',$$

or since both N_r' and N_v' are negative

$$|N_r'| > K|N_v'|. \quad . \quad . \quad . \quad (5)$$

Similarly from the lateral force curves a corresponding condition

$$|Y_r' - 1| < K|Y_v'| \quad . \quad . \quad . \quad (6)$$

The significance of these conditions when applied to *Fig.* 6 is simple. When $|N_r'| > K|N_v'|$ then the line 1/R plotted against β is steeper at $\beta = 0$ than the curve $-N_\beta'/N_r'$ (rudders amidships) and the two curves intersect only when $\beta = 0$. If, on the

At very small rudder angles on unstable ships matters are rather more complicated, and it is conceivable that an airship may turn to starboard with the rudders slightly to port.[1]

In pitch similar considerations would apply, but both the equilibrium equations 1 and 2 in that case contain gravity terms which do not vary with speed, and in addition terms depending on the trim of the airship would be introduced.

§ (25) STABILITY IN CURVILINEAR FLIGHT.—The criterion for lateral stability in rectilinear flight, based on the Mathematical Theory of Small Oscillations, is

$$Y_v N_r > N_v(Y_r - u_0). \quad . \quad . \quad (7)$$

(See "Aircraft, The Stability of," for a full discussion), with a similar condition for

[1] *A.R.C., R. and M.* 716.

longitudinal stability. It may be pointed out that if conditions (5) and (6) be satisfied then (7) is also satisfied.

For the most general motion of an airship no simple stability criterion is available. The solution of the problem depends on an equation of the eighth degree, the coefficients in which are exceedingly cumbrous functions of the resistance derivatives. The calculations can, however, be considerably simplified for the case of turning in a horizontal plane, provided that it be assumed that the small motions in pitch and roll can be neglected. Such assumptions are apparently justifiable in view of the fact that the results of experiments on models at zero angles of pitch and roll agree with observations on full scale, as far as concerns the determination of equilibrium conditions. The condition of stability corresponding with (7) may be written

$$\Delta = \begin{vmatrix} X_u & X_v+r_0 & X_r+v_0 \\ Y_u-r_0 & Y_v & Y_r-u_0 \\ N_u & N_v & N_r \end{vmatrix} < 0 \quad . \quad (8)$$

or $$X_u\Delta_1+(X_v+r)\Delta_2+(X_r+v_0)\Delta_3<0. \quad . \quad (9)$$

In this expression, X_u is negative, $(X_v+r_0)\Delta_2$ is negative, and (X_r+v_0) is probably negligible; both of the last two terms vanish in rectilinear flight and 9 reduces to 7.

The two terms in Δ_1 that vary rapidly with angle of yaw are Y_v and N_v, where

$$Y_v=-\frac{1}{V}\left(2Y_\beta \sin\beta+\frac{\partial Y_\beta}{\partial\beta}\cos\beta\right),^1$$

and similarly for N and X. Since the angle of yaw β is never greater than about 7° the predominant term in the expression in the brackets is $\cos\beta\,.\,\partial Y_\beta/\partial\beta$, and this increases with β. On the other hand $\cos\beta\,.\,\partial N_\beta/\partial\beta$ decreases with β. See *Figs.* 4 and 5. N_r also increases with β, and Y_r-u_0, if it varies at all, decreases with β, so that

$$\Delta_1=Y_vN_r-(Y_r-u_0)N_v$$

increases with β.

If therefore $\Delta_1>0$ for rectilinear flight, it will also be greater than zero for curvilinear flight, and hence $X_u\Delta_1<0$. $(X_v+r_0)\Delta_2$ is also less than 0, and therefore $\Delta<0$. Thus if an airship be stable in rectilinear flight it will be stable in curvilinear flight.

The converse, however, is not true; although $\Delta_1<0$ in rectilinear flight (*i.e.* the airship unstable) it may be, and probably always will be, greater than zero at the position of equilibrium in curvilinear flight, hence

$$X_u\Delta_1<0,$$

and since $(X_v+r_0)\Delta_2$ is always negative

$$\Delta<0.$$

A "sufficient" condition of stability in all cases appears, therefore, to be

$$\Delta_1>0,$$

[1] $Y_u=1/V[-2Y_\beta\cos\beta+\sin\beta(\partial Y_\beta/\partial\beta)]$.—*A.C.A., R. and M.* 171.

the values of the resistance derivatives being taken at the angles of yaw appropriate for equilibrium.

V. The Distribution of Pressure (Experiments on Models)

§ (26) General.—Problems arise from time to time, for the solution of which a knowledge of the distribution of normal pressure over the airship envelope is essential. Such problems include, in the case of the rigid airship, calculations of the stresses in the structure arising from aerodynamic causes, and, in the case of the non-rigid airship, the analogous problem of the determination of the nose stiffening required to prevent the envelope being pressed inwards at high speeds. The only available evidence regarding the pressure distribution over the hull is that obtained from experiments on models of various types of airship forms. These include models of the Parseval type,[2] of two rigid airship forms of a rather obsolete type [3] (with a long length of cylindrical body and high resistance coefficient), and of a more recent form.[4] Mention might be made also of a less complete set of experiments on a non-rigid form of low resistance coefficient,[5] and of an experimental and theoretical investigation [6] at zero incidence, conducted on a series of forms determined by the configuration of the flow (in ideal fluid) of a uniform stream past a system of sources and sinks.

Taken in order, four of these investigations deal with

(*a*) and (*b*) The pressure distribution on a model of the envelope only at various speeds at zero incidence, and that at one speed at various angles of incidence over the whole surface. The cross-section of the model was circular.

(*c*) The pressure distribution over the surface of a model with fins and without fins and cars at various speeds, angles of yaw and pitch, and a few observations of fin pressures. The cross-section of the model was polygonal.

(*d*) The pressure distribution on the envelope only at various speeds at zero incidence, and near the nose at one speed and several angles of incidence. The pressure distribution over a spheroid as determined by hydrodynamical methods is compared with that determined experimentally.

The investigation described in the first three cases includes an analysis of the results to determine the average pressures on the

[2] *A.C.A., R. and M.* 107, Fage and Stern, 1913.
[3] *A.C.A., R. and M.* 246, Pannell and Campbell, 1916.
[4] *A.R.C., R. and M.* 801, Jones and Bell, 1922.
[5] *A.C.A., R. and M.* 600, Jones and Williams, 1919.
[6] *Jahrbuch der Motorluftschiff-Studiengesellschaft*, 1911–12, Fuhrmann.

hull when yawed, and the longitudinal and lateral force due to normal pressures.

§ (27) The Method of Experiment.—The method in common use for determining the pressure distribution may be briefly described as follows. A piece of soft composition or hypodermic tubing sealed at one end is inserted in the airship model flush with the surface. Holes are bored in the tube at points where the pressures are to be found, only one hole at a time being left open. The other end of the tube is connected to one end of a Chattock manometer, the other side of which is connected to the hole in the side of the channel. It is thus possible to measure the difference between the pressure at the hole on the model and that at the hole in the side of the channel. The pressure required is the difference between the normal pressure at the point on the model and the static pressure in the channel at that point. Hence it is necessary to apply to the observations taken a correction equal to the difference between the static pressure over the surface of the model in the channel and the hole in the side. This correction varies along the channel (see § (6)).

With a model of circular cross-section with no fins or cars, it suffices to insert only one tube in the model, provided the model is mounted in the channel so that it can be rotated about its own axis and about an axis perpendicular to it, and provided also that the tube extends along the whole length of the model. In the case of a model of polygonal cross-section, particularly when fins and cars are attached, pitch and yaw are not interchangeable and tubes have to be inserted at intervals over the whole surface. Fourteen tubes were used in the experiments on a recent type of ship referred to above. Another method, which has been used for experiments on a kite balloon model, is to employ a hollow metal model with holes bored into the interior.

§ (28) Deduction of Form Resistance, Longitudinal Force and Lateral Force.—Taking the origin and axes as in § (9), let the normal pressure at any point P on the surface be denoted by p; and let the plane xOP make an angle ϕ with xOz, and r be the distance of P from Ox, then the average pressure at the section x = constant (through P)

$$= \frac{1}{2\pi}\int_0^{2\pi} p d\phi.$$

The resultant pressure along Ox (*i.e.* the longitudinal force, or form resistance if the angle of yaw be zero) is

$$\int_{s_1}^{s_2}\int_0^{2\pi} p d\phi \,.\, r\cos\theta\, ds,$$

ds is the element of length along an axial section through P, s_1 and s_2 are the values of s at the head and tail respectively, and θ the angle between the normal at P and the axis of x.

Since $dr = \cos\theta\, ds$, the above integral can be written

$$\int_{0_1}^{0_2}\int_0^{2\pi} p d\phi \,.\, dr,$$

where the limits 0_1 and 0_2 refer to the zero values of r at the head and tail.

If the ship be a solid of revolution whose axis is the axis of x, then when the angle of yaw is zero, p and r are independent of ϕ and the integral reduces to

$$\pi\int_{0_1}^{0_2} p \,.\, d(r^2) \quad \text{or} \quad \int_{0_1}^{0_2} p \,.\, dA,$$

A being the area of the section whose radius is r.

Now to determine the lateral force and yawing moment, we note that the component of p in the plane xOy is $p\sin\phi$. Hence the resultant pressure in the plane xOy on the cross-section through P is

$$-\int_0^{2\pi} p\sin\phi \,.\, r d\phi = \int_{-z_0}^{z_0} p \,.\, dz = \mathrm{P},$$

where z_0 is the maximum value of z at the section through P (*i.e.* the radius).

The resultant lateral force is

$$\int_{s_1}^{s_2} \mathrm{P}\sin\theta\, ds = \int_{x_1}^{x_2} \mathrm{P} dx.$$

Similarly the yawing moment is

$$\int_{x_1}^{x_2} \mathrm{P}x \,.\, dx.$$

Examples are given below of the nature of the quantities considered.

§ (29) Average Pressures and Longitudinal Force. Skin Friction.—*Fig.* 7 shows the average pressures on a model of a rigid airship in the absence of fins and cars at angles of yaw of 0°, 4°, 10°, and 15°. The curves may be taken as representing the type of distribution which had been found for models of airship hulls. In those with bluff heads and tails the changes are confined to shorter lengths, whereas for models with finer extremities the region in which the pressure is changing, is extended and the curves become less steep. An interesting feature of the results is the decrease in average pressure (*i.e.* an increase in suction) with increasing angle of yaw.

The determination of longitudinal force results in the conclusion that the force due to normal pressures approximates to zero. A result of this nature indicates the impossi-

bility of calculating the resistance of a streamline body by the use of a "skin-friction" coefficient determined on a plane surface and friction coefficient determined at N.P.L. in a preliminary experiment on plate glass, the calculated resistance was found to be of the

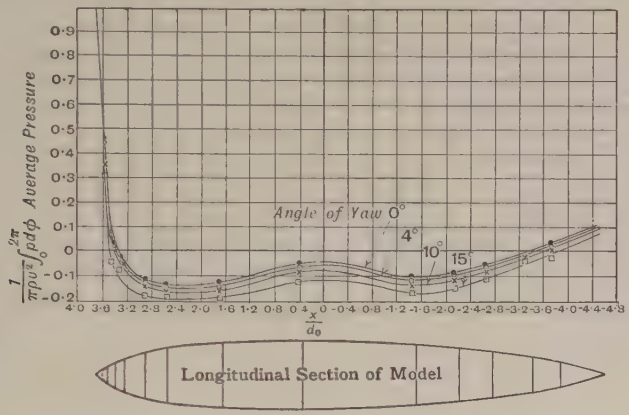


FIG. 7.

assumed to depend only on the roughness of the surface.

It follows from the experiment quoted above that the whole resistance of the body under consideration is due to the tangential force; and since the resistance varies greatly with changes of form it is evident that *the skin-friction resistance will depend on the form of the body*. In this connection it may be of interest to mention a calculation of the resistance of a body whose coefficient of resistance, determined by direct measurement, was 0·007. From the surface area of the body and a skin-friction coefficient determined at N.P.L. in a preliminary experiment on plate glass, the calculated resistance was found to be of the order of twice that measured in the wind channel.

§ (30) LATERAL FORCE AND YAWING MOMENT.—The distribution of resultant pressures—*i.e.* $\int_{-z_0}^{z_0} pdz$ (§ (28))—plotted against x is shown in *Fig.* 8 at different angles of yaw. The lateral force derived from an integration

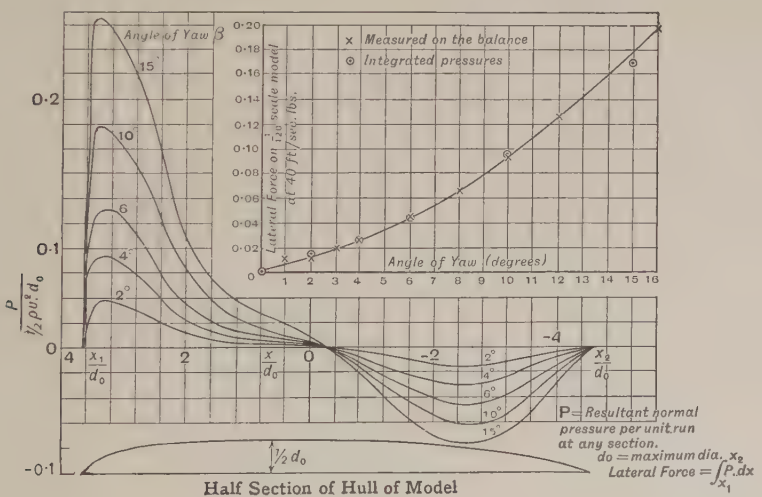


FIG. 8.

of these curves is also shown in comparison with the lateral force obtained by measurements on the balance. The agreement is shown to be remarkably good, and indicates that the lateral force is due entirely to normal

pressure and not to skin friction. The same agreement also obtains between the moments derived by two methods as above. It should, perhaps, be mentioned here that in the case of the experiments on the Parseval and on the older rigid airship models the integrated lateral force does not agree with that measured to the same degree as the above. This may be due to a peculiar characteristic of the hull under test; the lateral force per unit area is rather less than the mean given in *Fig.* 3, § (18).

§ (31) Speed Effect, Car Effect, and Fin Effect.—The pressure coefficient does not appear to vary consistently with speed, except perhaps near the tail where the coefficient decreases.

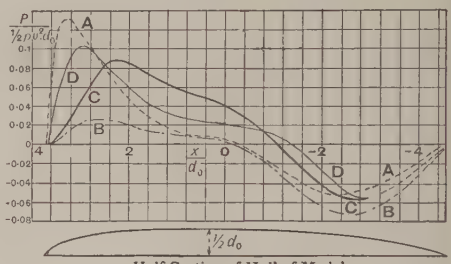
The effect of cars and fins is small except in their immediate neighbourhood, and the integrals are not greatly affected thereby.

§ (32) Comparison with Hydrodynamical Theory.—In the reports referred to in § (26) it is shown that the pressures over the forward end of a stream-line model agree very well with those calculated from ideal fluid theory. The agreement breaks down completely near the after-end. In the case considered at the N.P.L. (viz. a spheroid), agreement was good for about three-fourths of the length of the spheroid. Moreover, the pressures over an airship head whose form approximates to a spheroid agree with the theoretical pressures over the spheroid, and it is concluded that the latter can be used for nose stiffening calculations.

§ (33) The Distribution of Pressure in Curvilinear Flight.—It is to be borne in mind that the specimen curves shown in *Figs.* 7 and 8 apply to an airship in purely translational motion. These curves undergo an appreciable modification when the translation is associated with rotation. No experimental data are available to indicate the nature of such a modification. The following method of estimating the form taken by the curves of *Fig.* 8 in steady circling flight has been suggested.[1]

It has been shown that the areas of these curves give the lateral force due to translation and that the areas of a corresponding set give the yawing moment due to translation. Now, knowing Y_r/V due to the hull (§ (22)), and, from experiment, CN_r/V due to the hull, the total force and moment in circling flight can be deduced. Having decided on the values of r and β (§ (23)), let the curves of distribution of resultant pressure for the appropriate β with $r=0$ be so modified as to give the correct total lateral force and yawing moment. Thus a distribution of resultant pressure consistent with the known resultant force and moment is derived. Assume now that near the nose of the model the pressures calculated by purely hydrodynamical methods for pure translation and for combined translation and rotation bear the same relation to each other as in actual fluids; find the pressures (in the two ideal fluid cases) over the spheroid to which the head of the airship model approximates, and use the resulting curves as a guide in drawing the pressure distribution curve near the nose of the model; the knowledge of the resulting lateral force and moment will probably then be sufficient to limit the shape of the curve for the remainder of its length to a reasonable degree of accuracy.

Curves A, C, and D of *Fig.* 9 show the type



Half Section of Hull of Model

Fig. 9.

of curves obtained for an angle of yaw of 7·3°. Curve A has been obtained from *Fig.* 8 by interpolation, and represents the resultant pressure distribution in rectilinear motion ($r=0$). Curves C and D are curves obtained for curvilinear motion and give the correct total force and moment, use having been made of theoretical calculations on a spheroid in determining the latter curve.

It may be mentioned that a "strip theory" applied to the airship hull appears to be unsound. It gives a value of Y_r due to hull which cannot be believed, and a value of CN_r due to hull which is double that obtained experimentally. (See curve B of *Fig.* 9.)

§ (34) Pressures on the Fins.—In conclusion, mention may be made of further experiments conducted to determine the fin pressures on a model of another recent ship.[2] The results confirm the conclusions based on experiments on full scale, and together with the observations referred to in § (26) show that the pressures increase rapidly with angle of yaw.

J. R. P.
R. J.

[1] *A.R.C., R. and M.* 780, "Aerodynamic Pressure on an Airship Hull in Curvilinear Flight," Jones, 1921.

A.R.C., R. and M. 808, Williams and Bell.

AIRSHIPS, LIFT OF, UNDER VARYING CONDITIONS

The buoyancy of an airship depends upon the weight of air displaced and the weight of the ship and the gas she contains. The variation which most influences the lift of the ship is, therefore, that of the density of the surrounding air.

§ (1) Variation of Atmospheric Conditions with Height.—It is common knowledge that the pressure and temperature of the atmosphere at sea-level vary with time and place. So also does the rate at which these quantities vary with height.

If the variation of temperature with height, and the sea-level temperature and pressure, are known, the pressure and density of a dry atmosphere at all heights are also known, since we have [1]

$$\frac{dp}{dh} = -g\rho = -\frac{gp}{R_a T},$$

and therefore

$$\int \frac{dp}{p} = -\frac{g}{R_a}\int \frac{dh}{T},$$

where p is the pressure at any height,
T is absolute temperature,
R_a is the "gas constant" for air ($p = R\rho T$),
h is height,
g is acceleration due to gravity,
ρ is density.

The temperature usually decreases with increase of height at a mean rate of about $1\frac{1}{2}$ to 2° C. per 1000 feet up to about 35,000 feet above sea-level, beyond which it is almost independent of height and has a value of about 220° C. abs. (Europe).

The temperature gradient, however, varies considerably, and is frequently reversed in the lower layers of the atmosphere.

Humidity of the atmosphere causes a decrease of density. This effect is usually treated as negligible in Europe, whilst it causes an appreciable decrease of density near the ground in tropical climates.[2]

In consequence of these variations of atmospheric temperature, pressure, and density it is usual to adopt a conventional atmosphere for purposes of comparison and prediction of aircraft performance and for calibration of barometric altimeters. Various such conventional or "standard" atmospheres have been proposed and adopted by various authorities in different countries. In some of these an arbitrary and uniform temperature gradient with height is assumed, intended to represent average conditions in the region concerned. In England the standard atmosphere most generally adopted at present is a mean of a large number of observations made over a long period at a number of stations in the south-east of England. This standard has an irregular temperature gradient. It is given in Table X. of *Geophysical Memoirs*, No. 13, referred to above; also in *Reports and Memoranda*, No. 509, of the Aeronautical Research Committee.[3]

The convention on which English altimeters (aneroid barometers graduated in height) are calibrated is that of an uniform temperature of 10° C. at all heights. This differs considerably from average conditions and from the "standard" atmosphere just described. The use of the assumption of a constant temperature of 10° for this purpose dates from a time when few reliable observations of the upper atmosphere were available (see *Reports and Memoranda*, No. 610, Aeronautical Research Committee).

§ (2) Lift of an Airship.—The "lift" of an airship is the difference between the weight of air displaced by the gas and the weight of the gas itself, and is given by volume occupied by the gas × (density of air − density of gas).

Let V be the total volume of the gas-bags when completely distended,
p be the pressure of air or gas,
T be the absolute temperature,
ρ be the density,
R be the gas content $= p/T\rho$,
and let the suffix a refer to air,
g refer to gas,
o refer to sea-level conditions for the "standard atmosphere."

Also let $\Delta = \rho/\rho_o = pT_o/p_oT$ = relative density, and let Δ_h be the value of the relative density of the gas at which a given mass of gas in an airship at the time considered completely fills the gas-bags.

Then the "lift" per unit weight of gas[4] is

$$\frac{\rho_a}{\rho_g} - 1, \text{ or } \frac{R_g T_g}{R_a T_a} - 1,$$

and the total weight of gas is

$$\frac{V p_o}{R_g T_o}\Delta_h,$$

so that the lift of an airship may be expressed as

$$\frac{V p_o}{R_g T_o}\Delta_h\left\{\frac{R_g T_g}{R_a T_a} - 1\right\},$$

which may be written in the form

$$V\rho_{ao}\Delta_h\left[\left(1 - \frac{R_a}{R_g}\right) + \left(\frac{T_g - T_a}{T_a}\right)\right].$$

[1] See article "Atmosphere, Physics of," Vol. III.

[2] See "The Characteristics of the Free Atmosphere," *Geophysical Memoirs*, No. 13, published by the Meteorological Office.

[3] See also "Barometers and Manometers," §§ (16), (17), Vol. III., and "Aircraft, Performance of," § (2).

[4] The difference between the mean absolute pressure of the gas in an airship and that of the surrounding air is small and is usually disregarded in lift calculations. The difference will not usually exceed 1 millibar for rigid airships, or $2\frac{1}{2}$ millibars for non-rigid airships.

Here the term $(1-(R_a/R_g))$ depends upon the quality of the gas.

If the ratio $\frac{(1-(R_a/R_g))}{(1-(R_a/R \text{ for pure hydrogen}))}$ be denoted by K, the expression for lift becomes

$$V\rho_{a_0}\Delta_h\left[\cdot 9305K + \left(\frac{T_g - T_a}{T_a}\right)\right] \quad . \quad (A)$$

for $\frac{R_a}{R \text{ for pure hydrogen}} = \cdot 0695.$

The factor K is usually termed the " purity " of the gas. Alternatively, if σ be the ratio of density of actual gas/density of pure hydrogen, the lift is given by

$$V\rho_{a_0}\Delta_h\left(\frac{T_g}{T_a} - \cdot 0695\,\sigma\right). \quad . \quad . \quad (B)$$

If we assume the density of the air to be ·073 lb. per c. ft., that of pure hydrogen ·0053 lb. per c. ft., then at a pressure of 30 inches and a temperature of 60° F. the lift will be 71 lbs. per 1000 c. ft. This, however, is too great, for the hydrogen is never pure, and for design purposes a figure of 68 lbs. per c. ft., which corresponds to a purity of 95·47 per cent, is usually assumed and is found to be fairly representative of the conditions met with in airship practice.

Inspection of the expression (A) or (B) shows that:

(i.) If the ratio of the temperatures of the gas and of the surrounding air be constant, the lift of an airship will be constant so long as no gas is discharged (*i.e.* Δ_h constant).

(ii.) When the ship rises above the height at which the gas-bags become full, gas must be discharged and the value of Δ_h is thereby reduced. As the ship continues to rise the value of Δ_h falls off in the ratio of p to T_g, and this is proportional to p/T_a (still assuming T_g/T_a to be constant). Hence the lift decreases in proportion to the density of the displaced air.

(iii.) The effect of " superheating," *i.e.* raising the temperature of the gas above that of the air, is to cause an increase in the volume of the gas and therefore in the weight of air displaced, the weight of gas remaining unchanged. This produces an increase of lift given by $V\rho_{a_0}\Delta_h(T_g - T_a)/T_a$, which is independent of the density of the gas.

(If, however, a ship be just full of gas, and the gas temperature be increased by δT_g whilst the temperature and pressure of the air remain unaltered, the resulting increase in volume of the gas will be discharged through the automatic valves and the alteration in lift will be a small increase equal to the weight of gas lost, which is

$$V\rho_{a_0}\Delta_h\frac{R_a}{R_g}\frac{\delta(T_g)}{T_g}.\Big)$$

§ (3) SUPERHEATING.—In practice, with the present type of outer cover, the temperature of the gas may be as much as 15° C. above that of the air. A difference of 5° to 10° is common. This superheating of the gas is chiefly due to solar radiation being absorbed by the material of the gas-bags and thence transferred to the gas by conduction and convection. When a ship is flying under given conditions the temperature of superheat increases until the rate of loss balances the rate of absorption. The size of similar ships does not alter the temperature of equilibrium, but increase of size increases the time taken to reach this equilibrium.

Another cause of temporary superheating is rapid ascent and descent of an airship. The consequent rapid expansion or contraction of the gas takes place under conditions approximating to those of adiabatic change of volume. The adiabatic rate of change of gas temperature with height or dT_g/dh may be shown to be $g/R_a(\gamma - 1/\gamma)T_g/T_a$, where γ is the ratio of specific heats of the gas, h is height, and the remaining symbols have the meanings previously assigned. This is approximately 3° C. per 1000 feet for a hydrogen-filled ship in air. A rate of change of $-2\frac{1}{2}$° C. per 1000 feet has been observed, when other conditions have been such as to maintain $T_g - T_a$ constant. (The *air* temperature gradient on this occasion was $-1\frac{1}{8}$° C. per 1000 feet, and the rate of descent was 250 feet per minute.)

Superheating by solar radiation is usually disadvantageous in flight on account of its frequent variation. Repeated discharge of gas and ballast alternatively is clearly uneconomical, and in practice the excess or deficiency of buoyancy is met by an aerodynamic lift which is obtained when the axis of the hull makes a small angle with the line of flight. When, however, the hull of an airship is acting as an aerofoil in this way the resistance to forward motion is appreciably increased.

F. M. R.

AIRSHIPS, equilibrium of, conditions of, and determination of positions of, in curvilinear flight. See " Airships, Experiments on," § (24).

Performance of. See " Aircraft Performance," § (10).

Stability of; mathematical treatment. See " Aircraft, The Stability of," § (13).

ALTIMETER: an instrument, working on the principle of the aneroid barometer, designed to indicate the approximate height above ground. See " Aircraft, Instruments used in," § (2).

ALTIMETERS, errors of. See " Aircraft, Instruments used in," § (3).

Variation of pressure due to the speed of the aircraft. See *ibid.* § (3) (v.).

ALTITUDE, effect of, on ignition of aircraft engines. See "Engines for Aircraft, Effect of Altitude," § (5).
Effect of, on cylinder cooling of aircraft engines. See *ibid.* § (6).
Effect of, on fuel consumption of aircraft engines. See *ibid.* § (3).
Effect of, on power of aircraft engines. See *ibid.* § (2).
Effect on carburation of aircraft engines. See *ibid.* § (4).

ANGLE OF YAW: the angle between the flight path and the longitudinal axis of an aeroplane or airship.
Measurement of, on airships in flight. See "Airships, Experiments on," § (11).
Calculation of, from experiments on models. See *ibid.* § (24).

ASPECT RATIO. See "Aeroplane, Component Parts of."

ATMOSPHERIC ELECTRICITY, PROTECTION OF AIRSHIPS AND KITE BALLOONS FROM

A VERY considerable electrical discharge may pass through a kite balloon or an airship if moored to the ground by a steel wire, due to the potential differences in the atmosphere or to a potential difference induced by a discharge in the neighbourhood or by a direct lightning stroke.

There are two methods of endeavouring to avoid damage by such a discharge. One is to insulate the system as far as possible, the other is to make the whole system a good conductor so that the discharge passes without harm.

The first system is difficult because the voltages are extremely high, and the insulators must become wet under certain circumstances. C. T. R. Wilson gives the potential difference [1] which probably exists in the neighbourhood of a thunderstorm as 20,000 to 30,000 volts per metre or one-hundredth of that which would be necessary to produce a direct spark. The insulating gaps which would have to be preserved in the cable of a kite balloon flying at say only 2000 ft. would have to be equivalent to an air-gap of 20 ft., and therefore become almost impracticable.

The second system is the one most usually adopted, but in order to obtain safety it is most necessary that the metallic circuits should be as thorough as possible, not only in the case of the direct passage from the highest point to the ground, but between all isolated metallic parts of the system such as valves. This method has the additional advantage that, the resistance of the system being small, a continuous discharge can take place, and thereby reduce the danger of serious accumulation of potential difference.

[1] See "Atmospheric Electricity," § (23), Vol. III.

§ (1) KITE BALLOONS.—In the case of kite balloons as used on service great care was exercised to earth the lower end of the cable and to bond all parts of the rigging. It was still, however, found that in spite of these precautions the envelopes were frequently struck. Observation showed that in the case of many balloons destruction was due to a discharge which was either induced by a lightning stroke in the neighbourhood or more frequently was associated with no visible flash at all. Destruction by a direct flash to the balloon itself was very rare.

The conductivity of the envelope fabric was examined, and it was ascertained that the surface, which is covered with particles of aluminium suspended in rubber or dope, was subject to a kind of coherer effect; the electrical resistance could be changed from a comparatively low value almost to infinity by a discharge in the neighbourhood. The presence of a film of moisture on the inner surface of the fabric may also have formed a somewhat erratic conductor, and caused the discharge to pass into the interior of the balloon.

Discharger bands were therefore fitted with sharp discharger points, and were placed over the highest point of the balloon with good metallic connections leading down to the wire rigging.

This system was applied to a number of balloons and was found to be effective, but the experience obtained with it before the Armistice was not sufficient to allow the results to be regarded as conclusive.

§ (2) AIRSHIPS.—The case of an airship in free flight is somewhat different, because she is not connected to earth. A discharge through her is only likely if through being a conductor she reduces the resistance between two clouds or two points between which a considerable potential difference exists.

All parts of the structure of an airship are, in any case, electrically bonded as thoroughly as possible, because this is necessary in order to avoid danger from sparking induced by the ship's wireless. This bonding must be carried out with care and great thoroughness, and it is important that the bonding wires should be led as direct as possible and not coiled into a spiral, as is frequently done in electrical work. The inductive resistance of such a spiral may render the bond definitely dangerous.

Considerable warning of the presence of electrically charged clouds can be obtained from the "atmospherics" heard in the wireless installation. When these "atmospherics" become excessive, it is desirable to wind in the ship's wireless aerial, which normally hangs down a distance of several hundred feet.

Cases have been reported in which a flash to earth has taken place from the rope which is first dropped when the airship lands. In certain cases the first man to touch the car of the ship has received a shock, if the rope has not been previously dropped or if it is very dry. It is not thought, however, that the ship carries a charge very long, as it is probably rapidly dispersed through the highly ionised exhaust if the motors are running.

Several airship officers have reported visible flashes in the immediate neighbourhood of ships in flight. In some cases the wireless aerial has been burnt when not hauled in sufficiently quickly. A clearly visible flash is reported to have passed from end to end of one rigid airship. No fire resulted, but on landing it was found that a hole had been fused in the bow plate and that the girders which carried the plate were fused together.

A rigid airship secured by the bow to a steel mast rode out a lightning storm of quite exceptional intensity with vivid flashes of lightning quite close to the ship. A non-rigid airship flying on the outskirts of the same storm was destroyed by fire in circumstances which were not of course explained, but were very possibly of electric origin.

The danger to an airship from atmospheric electricity therefore appears small, especially if the structure of the ship is of metal and all parts are correctly bonded. The principal danger from electric storms probably arises from the very violent atmospheric disturbances which accompany them, and are liable to damage the ship mechanically.

See also various reports to Advisory Committee for Aeronautics, 1919 and 1920.

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ATTACK, ANGLE OF. See "Aircraft: Explanation of Terms in Common Use."

AUTO-ROTATION OF AIRCRAFT. See "Model Experiments in Aeronautics," § (8) (v.).

AXES OF REFERENCE FOR AIRCRAFT. See "Aircraft: Explanation of Terms in Common Use"; also "Aircraft, Stability of," § (2).

B

BALLONS-SONDE: small balloons sent up with instruments for taking meteorological observations. See "Aircraft, Instruments used in," § (2).

BALLOON FABRICS, permeability of. See "Diffusion through Membranes," § (4).

BANK, ANGLE OF. See "Aircraft: Explanation of Terms in Common Use"; also "Aircraft, Stability of," § (2).

BENDING MOMENTS IN WING SPARS DUE TO NORMAL LOADING. See "Aeroplane Structures, Theory," § (10).

BENDING OF SPARS IN PLANE OF WING. See "Aeroplane Structures, Theory," § (12).

BUBBLE SEXTANTS AS USED ON AIRCRAFT. See "Aircraft, Instruments used in," § (10) (ii.).

C

CALIBRATION ERRORS IN AIRCRAFT INSTRUMENTS. See "Aircraft, Instruments used in," § (3) (iii.).

CALIBRATION OF ALTIMETERS: errors due to variation of atmospheric temperature and pressure. When calibrating altimeters some definite assumption is made regarding the variation of pressure with height; if these assumed conditions do not occur it follows that there must be an error in the instrument reading. See "Aircraft, Instruments used in," § (3) (iv.).

CAMBER. See "Aeroplane, Component Parts of."

CHORD OF THE WING. See "Aeroplane, Component Parts of."

CINEMATOGRAPH CAMERA, the use of, in full-scale research on aeroplanes. See "Aerodynamic Research, Full Scale," § (24).

CLIMBMETER: an instrument used on aircraft for indicating the rate of climb at any moment. See "Aerodynamic Research, Full Scale," § (6), and "Aircraft, Instruments used in," § (1).

CONSTANT-FLOW method of testing balloon fabrics. See "Diffusion through Membranes," § (6).

CONSTANT-VOLUME method of testing permeability. See "Diffusion through Membranes," § (8).

CONTINUOUS BEAMS, reaction at supports of. See "Aeroplane Structures, Theory, § (9)."

CONTINUOUS BEAMS UNDER END THRUST. See "Aeroplane Structures, Theory," § (8).

CONTROL AND STABILITY OF AIRSHIPS, based on the results of experiments on models. See "Airships, Experiments on," § (17) *et sqq.*

CONTROL OF AN AEROPLANE, general. See "Aerodynamic Research, Full Scale," § (21).

CONTROL SURFACES, efficiency of, on airships. See "Airships, Experiments on," § (22).

CONTROLS, effect of small movements of, on aircraft stability; mathematical treatment. See "Aircraft, The Stability of," § (15).

COTTON as used for aircraft. See "Aeroplane Wings, Fabrics for," §§ (1) and (12).

COUNTS OF YARN AND OF FABRIC. See "Aeroplane Wings, Fabrics for," § (4).

— D —

DEFLECTION OF STRUCTURES. See "Aeroplane Structures, Theory," § (17).

DENSITY OF AIR, CORRECTION FOR, as applied to aircraft instruments. See "Aircraft, Instruments used in," § (6) (i.).

DIFFUSION, LAWS OF. See "Diffusion through Membranes," § (2).

DIFFUSION THROUGH MEMBRANES

§ (1) HISTORICAL.—Almost as soon as Mitchell discovered a method by which small toy balloons could be made of thin unvulcanised rubber, he observed in 1831 that such balloons, even when apparently free from mechanical defects, were permeable to gases. His paper on the subject was reprinted in the *Roy. Inst. J.*, 1831, (2) 101 and 307, from the *Philadelphia Journal of Medical Sciences*. He made roughly quantitative experiments, allowing various gases to diffuse into air enclosed in a funnel bounded by a thin rubber film. The rates of diffusion which he observed, approximately corrected, in the light of later knowledge for the back diffusion of air but not for change in partial pressure difference, and referred to the rate for hydrogen as unity, were as follows:

Ammonia	32
Sulphuretted hydrogen	13
Cyanogen	10
Carbon dioxide	5·9
Nitrous oxide	5·0
Arseniuretted hydrogen	1·3
Ethylene	1·3
Hydrogen	1·0
Oxygen	0·6
Carbon monoxide	0·3

He also observed that rubber is capable of absorbing its own volume of carbon dioxide, undergoing slight swelling during the process. He pointed out that Graham [1] was in reality the first to notice a similar phenomenon in the case of a bladder partly full of coal-gas which became inflated when placed in an atmosphere of carbon dioxide; but Graham did not at the time extend his observations to other gases or membranes.

In spite of the republication of Mitchell's paper, the importance of the above property of indiarubber in connection with quantitative physical and chemical experiments was not, it appears, widely recognised. Peyron [2] presented the results of a number of tests to the Paris Academy of Sciences, showing that air leaked into a vacuum through a rubber sheet, and that hydrogen, carbon dioxide, and nitrous oxide, confined by membranes or tubes of rubber, passed out into the air, the latter also mixing with the contained gas. He pointed out that great improvement in gas-tightness could be secured by "doping" the rubber with linseed oil. In the discussion at the meeting Chevreul and Dumas were inclined to disbelieve the possibility of appreciable leakage in chemical experiments, the latter savant asserting that he had used many rubber joints in his apparatus for the analysis of air and water and was satisfied that no leakage occurred.

§ (2) LAWS OF DIFFUSION.—It was, however, reserved for Graham in 1866 [3] to make the first accurate quantitative measurements in connection with his classical researches on diffusion through porous septa. After establishing his well-known law of diffusion for such porous bodies as gypsum, graphite, etc., he was led to study colloidal septa such as rubber, gelatine, gutta-percha, and oil-varnish films. By fastening a film of rubber over a thin stucco plate which closed a long wide tube, filling the tube with mercury and inverting, he was able to measure, from the rate of fall of the mercury, the rate at which gases surrounding the top of the tube passed through the film into the originally vacuous space above the mercury. The rubber films were cut from a toy balloon, and were unvulcanised: their thickness was about ·012 mm. The rates at which the gases entered, taking that of hydrogen as unity, were found to be

Carbon dioxide	2·46
Oxygen	0·464
Methane	0·391
Air	0·209
Carbon monoxide	0·202
Nitrogen	0·182

He noticed the large effect of temperature on the rate of diffusion in the case of a rubber-proofed silk fabric, the rate for air increasing from 0·56 c.c. per m.^{2} per min. at 4° C. to

[1] *Roy. Inst. J.*, 1829.

[2] *Comptes Rendus*, 1841, xiii. 820.

[3] *Roy. Soc. Phil. Trans.* p. 399.

2·25 c.c. at 20° C. and to 6·63 c.c. at 60° C. He made a large number of tests in the endeavour to utilise his results for the "dialytic" separation of gases: in the course of these tests he observed that oxygen and nitrogen have different temperature coefficients of diffusion, since the percentage of oxygen in his "dialysed air" was 41·6 at 20° C. and increased to 47 at 4° C.

Since the rates of diffusion or "dialysis" bore no apparent relation to the densities of the gases, he proposed the theory that the gases were "liquefied" or dissolved in the rubber, and in accordance with this conception he found that at about 15° C. rubber absorbed 0·78 of its volume of carbon dioxide or 0·068 of its volume of oxygen.

Peyron's warnings were independently confirmed by Aronstein and Sirks,[1] in so far as the leakage of hydrogen was concerned: they demonstrated that there was measurable loss of hydrogen through rubber tubing, either vulcanised or unvulcanised, when the thickness was 1·2 to 1·6 mm. They obviated this defect by doping the tubes with asphalt solution.

About ten years later Exner propounded his "law" to explain in the first place the differences observed in the rates of diffusion of gases and vapours through soap films.[2] The law stated that the velocities of passage of the gases through such films were proportional to $A/\sqrt{\rho}$, where A is the absorption coefficient of the soap solution and ρ is the density of the gas: the observed and calculated values of the velocities for nitrogen, hydrogen, carbon dioxide, etc., agreed within about 3 per cent; but oxygen diffused about 20 per cent faster than the law demanded, and the law did not apply at all to ether vapour. Only very rough agreement with the law was found by Pranghe[3] for diffusion through lamellae of linseed oil.

The simplicity of Exner's law led Wroblewski[4] to adopt it as a basis for the explanation of the results obtained in the diffusion of gases through rubber. He proposed the equation

$$P = DA\frac{p_1 - p_2}{x},$$

where P is the permeability, c.c. per cm.^{2} per sec.
D is the constant of diffusion of gas in the rubber,
A is the absorption coefficient, c.c. of gas dissolved per c.c. of rubber at 1 atmosphere pressure,
p_1 and p_2 are partial pressures of the gas (fractions of an atmosphere) at the two sides of the membrane,
x is the thickness of membrane.

[1] *Zeitschrift für Chemie*, 1866, 260.
[2] *Pogg. Ann.*, 1875, (6), 155, v. 321, and Beiblätter to *Annalen*, 1878, ii. 199.
[3] Beiblätter to *Annalen*, 1878, ii. 202.
[4] *Wied. Ann.*, 1879, viii. 29.

This equation assumes (1) that the absorption is a process of simple solution, being independent of surface phenomena or adsorption, and consequently varying only with the partial pressure according to Dalton's law and, of course, also with the temperature, and (2) that within the rubber the ordinary law of diffusion, Fick's law, holds.[5] In order to test these assumptions he measured both permeability and absorption coefficients for certain gases with the same sample of red vulcanised rubber: for the latter determinations the rubber was in the form of sheets about 0·25 mm. thick, for the former the sheets were stretched until the thickness was only a few hundredths of a mm. From his figure for the density of the rubber, 1·0270, it would appear to have contained some 6 per cent of antimony sulphide plus sulphur. The values which he found for the absorption coefficients were

Nitrous oxide . . .	$1·9561 - 0·02665\,t$
Carbon dioxide . . .	$1·2779 - 0·01576\,t$
Hydrogen	$0·02050 + 0·004071\,t$
Air	$0·06075 + 0·003757\,t$

the gases used being saturated with water vapour. His permeability measurements were made with air on one side of the membrane, and were therefore corrected for the back permeability of air, assuming that D varies inversely as $\sqrt{\rho}$. From these corrected permeabilities, in conjunction with the above absorption coefficients, he deduced the values of the diffusion coefficients D at 14° C. as

	Cm.^{2}/Sec.
Nitrous oxide . . .	62×10^{-8}
Carbon dioxide . . .	61×10^{-8}
Hydrogen	352×10^{-8}

In view of the fact that Graham had found that hydrogen does not obey the inverse square root law with any exactness even for diffusion through a graphite plate, Wroblewski considered that the results were sufficient to establish the law for the diffusion of gases in rubber, the curious differences in permeability being due to the complication of this law by the widely different absorption coefficients of the gases.

Wroblewski's views as to the nature of the permeation process have formed the basis of almost all the later theoretical work on this subject, though his quantitative results have been called in question, *e.g.* by Hufner.[6] Hufner pointed out that if the rubber and the gases were dry the absorption of nitrogen and hydrogen by massive grey vulcanised rubber

[5] Throughout this article, from this point onwards, the words permeability (permeation) will be used to denote what Graham called colloidal diffusion, in order to avoid confusion with the ordinary processes of diffusion proper.
[6] *Wied. Ann.*, 1888, xxxiv. 1.

was negligible, *i.e.* less than 0·002 c.c. per c.c., so that the values given by Wroblewski are due to the presence of water in the rubber. He showed, however, that even in the absence of water rubber dissolves carbon dioxide to the extent of 0·69 volumes at 14° C. (cf. Wroblewski's value 1·06 volumes for the saturated system).

The problem was attacked again by Kayser,[1] who was struck by the smallness of the temperature range used by Wroblewski—5° C. or so—and was not satisfied as to the legitimacy of the method used by that investigator to correct for the back permeation of air. Kayser used for his absorption experiments films of vulcanised rubber, 0·25 mm. thick, having a specific gravity of 0·945; he determined the relation of the absorption coefficient to partial pressure in the case of carbon dioxide, and found that the coefficient (volume of gas reduced to N.T.P. absorbed by 1 c.c. of rubber) was proportional to the pressure within some 2 per cent over the range 125 mm. to 1125 mm. of mercury. For the variation of solubility with temperature he found

For carbon dioxide.

$$A_t = 1{\cdot}3507 - {\cdot}018081\,t + 0{\cdot}0_4 9213\,t^2,$$

For hydrogen.

$$A_t = {\cdot}01278 - {\cdot}00018\,t + 0{\cdot}0_5 113\,t^2,$$

over the temperature range 0° to 70° C. Equilibrium was attained within an hour, no further absorption occurring even after five days. These results appear to be moderately trustworthy, but the same cannot be said of the figures given for permeability, which are means of separate determinations varying by as much as 30 per cent from the mean. Thus when his values for specific permeability (c.c. per cm.^{2} per min. per cm. thickness) to carbon dioxide and to hydrogen of films 0·08 to 0·15 mm. thick are calculated for a temperature of 20° C., the ratio is only 2·1 to 1 instead of the 2·5 or 2·7 to 1 found by other workers. His equations for the variation of specific permeability with temperature were

Carbon dioxide.

$$P \times 10^6 = -5{\cdot}084 + 2{\cdot}9281\,t \qquad (9°\text{ C.} - 33°\text{ C.}).$$

Hydrogen.

$$P \times 10^6 = +5{\cdot}520 + 0{\cdot}8756\,t \qquad (13°\text{ C.} - 30°\text{ C.}).$$

These values are not corrected for the back permeation of air.

Reychler also demonstrated that the absorption by rubber of sulphur dioxide,[2] and of carbon dioxide,[3] is a process of simple solution to which the law of partial pressures applies. The latter measurements were made with considerable accuracy in order to disprove the suggestion of W. Ostwald that the Freundlich adsorption equation $A = Kp^n$ was necessary: the exponent n of pressure p, for which Ostwald proposed the value 1·02, was shown to be unity within the limits of error of the experiments. For the solubility of carbon dioxide at 20° C. in fine Para sheet-rubber of density 0·95 he found the value 1·06 c.c. per gm., or almost exactly 1 c.c. per c.c., the absorption being very rapid. The solubility of sulphur dioxide at 18·5° C. was 25·8 c.c. per gm. or 24·5 c.c. per c.c.: with this figure may be compared a determination by Chappuis[4] at 0° C. which gave 38·5 c.c. per gm. It is now known that most of the unsaturated hydrocarbons, to which category indiarubber belongs, are freely soluble in liquid sulphur dioxide. The loss in illuminating power of coal-gas rich in ethylene and benzene when passed through rubber tubing has been shown to be due to the solution of these vapours in the rubber, which dissolves up to 8·6 per cent of its weight of them under these circumstances.

Some of the premises of Wroblewski's theory were called in question by Grunmach,[5] who made experiments on the permeability of fairly thick rubber sheeting by carbon dioxide. The method he used was novel and simple: two glass bell-jars, the pressure in which could be measured, were closed with the sheets, and one was filled with carbon dioxide and weighed from time to time, the other jar, full of air, being used as a counterpoise. Corrections were applied for the increase in area and decrease in thickness of the rubber caused by the bulging of the membrane. He found that the rate of permeation fell to $\frac{1}{15}$ of its original value, while the pressure dropped from atmospheric to $\frac{3}{4}$ atmo., and that the gas-tightness of a 2 mm. sheet was only 2·5 times that of a 0·15 mm. sheet. Grunmach considered that his results proved that the permeability was not directly proportional to the pressure of the gas nor to the inverse of the thickness of the rubber; but he did not take into account the decrease in partial pressure of the gas during an experiment owing to back-permeation by air, and assigned the change in rate of loss of weight solely to the change in total pressure, leaving unexplained his own observation that the rate became practically zero when the pressure had fallen to $\frac{2}{3}$ of the original.

§ (3) Measurements of Diffusion.—Probably the most exact measurements of the rates of passage of various gases through stretched membranes of rubber of the type used by Graham, Wroblewski, etc., have recently been made by Dewar.[6] The complica-

[1] *Wied. Ann.*, 1891, xliii. 544.
[2] *Bull. Soc. Chim.*, 1893, (3), ix. 404.
[3] *J. Chim. Phys.*, 1910, viii. 3, 617.
[4] *Wied. Ann.*, 1883, xix. 21.
[5] *Phys. Zeits.*, 1905, vi. 796.
[6] *Roy. Inst. Proc.*, 1918, xxi. (3), 813.

tions introduced by the presence of a second gas on the other side of the membrane were avoided in his experiments by exposing one side to the gas under examination and producing a vacuum on the other side by means of liquid air; the volume of the gas was calculated from the rate of increase of pressure in the exhausted apparatus: to prevent undue distension of the rubber membrane this was supported by a close gauze. The characteristics of the rubber used are not mentioned beyond the fact that it was of sheet Para about 1 mm. thick stretched until it was some 0·01 mm. thick. He made measurements at a series of different temperatures for several of the gases; at 15° C. the rates relative to that of hydrogen as unity were:

Carbon dioxide	2·50
Hydrogen	1·00
Oxygen	0·36
Helium	0·31
Argon	0·23
Air	0·18
Carbon monoxide	0·17
Nitrogen	0·125

The absolute permeability by air varied for different films from 1·2 to 3·2 c.c. per sq. cm. per day.

His curves connecting the logarithm of permeability with temperature consist practically of two straight lines for each gas, intersecting at 0° C. The temperature coefficients at 15° C. were:

	Per cent. per 1° C.
Carbon dioxide	6·1
Hydrogen	5·4
Air	6·3
Helium	5·1

Oxygen had a higher and carbon monoxide a lower coefficient than air. Dewar points out that the increase in the value of the temperature coefficient below 0° C. may probably be ascribed to the effect of traces of water in the films.

Mention may be made here of an observation on the permeability of rubber by argon, which was made by Rayleigh.[1] He collected 3 lits. of the "air" which leaked through a rubber film, and found it to contain 37 per cent of oxygen; the gas left after removing the oxygen contained 1·93 per cent of argon. Since atmospheric nitrogen contains 1·19 per cent of argon, he concluded that the permeability of rubber by argon was greater than by nitrogen; allowing for the difference in partial pressures, the ratio would be 1·6 to 1 Using Dewar's ratio for the permeabilities by nitrogen and hydrogen, the permeability by argon would be 0·20 (cf. Dewar's 0·23) of that by hydrogen.

As Dewar's permeability determinations were not accompanied by measurements of the solubility of the various gases in the rubber used, it is not possible to make any deductions therefrom to support or contradict the theory of the process outlined by Wroblewski. A paper by Daynes has since appeared,[2] in which an attempt has been made to obtain figures for the actual rates of diffusion of certain gases in rubber from measurements both of the permeabilities and the absorption coefficients. The method of determining permeability is described in a later section (Shakespear apparatus): the absorption coefficients are deduced from the time interval required for the establishment of steady dynamic conditions when one face of the film is suddenly exposed to the gas in question while the other remains in contact with air. It is shown that under these conditions, the permeability being expressed as $P=DAp/x$ with the notation of § (2), the "lag" or time elapsing before the rate of increase of concentration of the gas in the air chamber becomes constant is $L=x^2/6D$, so that

$$PL=\frac{px}{6}A.$$

Hence A and D can be calculated from the observed values of P, L, and x.

Three vulcanised Para films were used by Daynes, of which the thicknesses varied from 0·3 to 1·4 mm. When 1/P and PL were plotted against x, and L against x^2, the observed points lay sufficiently well on a straight line to confirm the truth of the hypothesis of Wroblewski as to the nature of the phenomena of permeability. These experiments were made with hydrogen on one side and air on the other, and included tests at temperatures some 6° C. apart which showed that the absorption of hydrogen by rubber had a temperature coefficient of about 0·5 per cent per 1° C. at 18° C.: hence the much larger temperature coefficient of permeability (some 4 per cent per 1° C. in these measurements) is due to the effect of temperature on diffusion in the rubber: this is in accordance with the well-known fact that a high temperature coefficient is always found for the viscosity of viscous substances.

In the table on the following page are given the values found by Daynes for the absorption coefficient A, the diffusion constant D, and for the "specific permeability" Px (c.c. measured at 17° C. per cm.^{2} per sec. per 1 cm. thickness), for various gases, with films about 0·4 mm. thick, at 17° C. Except in the cases of oxygen and air, which required the use of hydrogen on the other side of the membrane, and gave less accurate results, the gas into which the permeation occurred was air.

[1] *Phil. Mag.*, 1900, xlix. 220.

[2] *Roy. Soc. Proc.*, 1920, xcvii. 286.

Gas.	Absorption Coefficient.		Specific Permeability.		Diffusion Constant.		Solubility in Water at 15° C., Rel. to H=1.	D$\sqrt{\text{Density}}$ Rel. to H=1.
	Absolute c.c./c.c.	Rel. to H=1.	Absolute.	Rel. to H=1.	Absolute.	H=1.		
Hydrogen .	0·0397	1·00	$26·7 \times 10^{-8}$	1·00	$7·23 \times 10^{-6}$	1·00	1·00	1·00
Carbon dioxide	0·86	21·6	$73·4 \times 10^{-8}$	2·75	$0·85 \times 10^{-6}$	0·12	53·0	0·55
Nitrous oxide	1·71	43·1	$121·0 \times 10^{-8}$	4·53	$0·72 \times 10^{-6}$	0·10	41·5	0·47
Air . .	0·043	1·08	$5·18 \times 10^{-8}$	0·194	$1·21 \times 10^{-6}$	0·17	1·09	0·45
Oxygen . .	0·091	2·29	$8·97 \times 10^{-8}$	0·336	$0·95 \times 10^{-6}$	0·13	1·82	0·37
Ammonia .	41·0	1032	$303·0 \times 10^{-8}$	11·3	$0·074 \times 10^{-6}$	0·010	40000	0·03

In comparing Daynes' figures for relative permeability with those of earlier workers it must be remembered that the films he used were thick and not stretched, so that the effects of imperfections in them were less marked. Presumably as a result of this the peculiar nature of the "colloidal diffusion" is more pronounced; thus he gives 2·75 for the ratio of permeabilities for carbon dioxide and hydrogen, whereas Dewar and Graham found 2·50 and 2·46. Compare also his figure 0·34 for the oxygen ratio with Dewar's 0·36 and Graham's 0·46.

It may be observed that hydrogen has the highest coefficient for diffusion in the rubber: the greater permeabilities by carbon dioxide, nitrous oxide, and ammonia are due to the much larger solubilities of these gases.

The last column of the table has been added to show how these measurements agree with the requirements of Exner's law; according to this the diffusion constants should be inversely proportional to $\sqrt{\text{density}}$, so that $D\sqrt{\rho}$ should be constant. Hydrogen and ammonia show very wide differences from the products given by the other gases; the "law" may be considered to be disproved.

The column of aqueous solubilities has been added in order to show the rough parallelism which exists between the relative solubilities of the gases in water and in rubber. Such similarities have been shown by Just,[1] Christoff, and others to hold for the solubilities of gases in the most diverse liquids provided that no combination is to be suspected. In general, gases are more soluble the higher their critical temperatures, but the simplicity of this relation is clouded by the volume changes occurring on solution and the effect of the compressibility of the solvent.

The inverse proportionality between permeability and thickness which is required on Wroblewski's hypothesis has also been shown by Edwards and Pickering[2] to hold within the accuracy which can be expected from the nature of the method of manufacture of the films used. From the figures obtained at 25° C. with films varying from 0·2 to 2·0 mm., Edwards deduces a specific permeability of $34·0 \times 10^{-8}$ c.c. of hydrogen measured at 0° C. and 760 mm. pressure per cm. area per cm. thickness per sec. The curve given by Daynes (*loc. cit.*) for a film 1·4 mm. thick gives on extrapolation to 25° C. a value of $46·0 \times 10^{-8}$ for the specific permeability of his rubber in the same units. Kayser's equation (*vide supra*) gives 55×10^{-8} for this temperature when his figure is increased by one-fifth to correct for the entrance of air; but since his thickest film was only 0·15 mm. thick, this value is likely to be high owing to imperfections in the film.

Wroblewski's theory also demands that the permeability shall be directly proportional to the partial pressure. In the paper above mentioned Edwards shows that this holds for the permeation of "dental dam" (thin sheet-rubber about 0·2 mm. thick) by mixtures of carbon dioxide and air in which the partial pressure of the carbon dioxide varied from 15 to 100 per cent of the total.

§ (4) Permeability of Balloon Fabrics. —In the foregoing *résumé* of the literature of the permeation of rubber membranes no mention has been made of the extensive work which has been carried out during the last two decades on the leakage of rubbered balloon fabrics. The use of these appears to have been first suggested by Tarcot in 1859, but the preparation of suitable material was not accomplished until about 1900. The nature of the difference between the behaviour of rubber when free and when supported on a textile will be considered at a later stage, but the methods of measurement of permeability of balloon fabrics are now to be described.

Permeability is expressed for practical purposes in litres per sq. metre per twenty-four hours, the volume being reduced to 0° C. and 760 mm. of mercury pressure; to convert values given in these units to absolute values in c.c. per sq. cm. per sec. multiply by $1·157 \times 10^{-6}$. As the specifications for balloon fabric in England were at first copied from French practice, there has fortunately never been any wide use of English units in this branch of testing. The maximum permeability allowed in modern specifications for rubbered

[1] *Z. phys. Chem.*, 1901, xxxvii. 342.
[2] *Bureau of Standards, Scientific Paper*, 1920, No. 387.

fabric for the envelopes of non-rigid airships or of kite-balloons is 10 lits. per sq. m. per day at 15°·5 C.

Apparatus have been constructed for the measurement of the permeability of balloon fabrics on three different principles :

(i.) A vessel is closed by a disc of the material under test, and is then filled to a measured volume with hydrogen ; the rate of escape of the hydrogen into the atmosphere is deduced from the decrease in volume at constant pressure. This will be called the " volume-loss " method. The complementary method, of observing the decrease in pressure at constant volume, which would allow some simplification of design, is not applicable owing to the extensibility of the fabric and to the possibility of the occurrence of viscous flow of the gas through small apertures.

(ii.) Constant currents of air and of hydrogen are allowed to flow over the two faces of the fabric, which is clamped between two flanged vessels. The resulting quantity of hydrogen in the air stream is then measured either by burning the hydrogen to water, which is weighed after a suitable amount has collected, or by determining the concentration of the hydrogen in the mixture by measurement of some physical property and noting the rate of flow of the mixed gases. These methods will be referred to as " constant flow " methods.

(iii.) The fabric being clamped as in (ii.) with pure hydrogen and pure air on the two sides, the air vessel is sealed and the *rate of increase* of concentration of hydrogen in the fixed volume of air is observed. This may be called the " constant volume " method.

§ (5) Volume-loss Method.—Until the year 1909 balloon fabrics were all tested on apparatus of the volume-loss type, although some of the defects of the principle were recognised. The reason was apparently that the construction of such apparatus is simpler, and at first sight appears to reproduce fairly well the conditions occurring in a balloon. Only one design of this type ever attained any wide use, viz. the Renard-Surcouf balance (*Fig.* 1), which is still employed on the Continent. The balance is so called from the means adopted for the maintenance of a constant pressure. A 30 cm. disc of the fabric is clamped at G so as to form the top of the bell of a species of gasometer : the bell is supported on one arm of a rough balance, and the requisite fraction of its weight can be counterpoised by weights I placed on a pan H on the other arm. The base of the balance supports the annular container A, which forms the lower half of the gasometer : the annulus is filled with water. The bell is filled with hydrogen (about 4 lits.) and by removing weights from the pan H the pressure indicated on the U-tube D is increased to the desired amount (usually 30 mm. of water in excess of the atmospheric). As the gas escapes the bell sinks in the annulus and the volume lost is calculated from the distance of fall, which is indicated by a pointer K attached to the axis of the beam. The chief virtues of the Renard-Surcouf balance for works purposes lay in the fact that it was robust and free from any fragile glass parts, and that it could be obtained ready for use from the Astra Airship Company.

Four other forms of volume-loss apparatus used by various airship firms and testing institutions are described by Austerweil [1] under the names of Lebaudy, Picard, Clement-Bayard-Sabatier, and Henri. Another is due to Josse.[2] In these a hydrogen chamber is closed by the fabric under test and is in communication with a measuring tube : the volume of gas escaping is equal to the volume of water or oil which has to be run into this tube to keep the pressure constant. The introduction of the water is effected by a levelling-tube or automatically by a Marriotte bottle or by a U-tube with constant head. For approximate results and for certain purposes apparatus of this type may still be useful. Convenient forms embodying the best points of the older constructions, together with improvements suggested by experience in permeability determinations by the constant-flow method, are described by the writer in *A.C.A. Techn. Rep.*, 1915–16 [3] (" Permeability of Airship Fabrics by Helium ") and 1916–17 (" Deterioration of Rubbered Balloon Fabrics under the Action of Light ").

The disadvantages of the volume-loss method are :

(i.) It measures not the actual volume of hydrogen lost but the difference between this and the volume of air which permeates inwards : in a comparison of values for the permeability at 25° C. of 9 different fabrics given by a volume-loss and by a constant-flow method Edwards [4] found that the former method indicated only about 71 per cent of the true permeability : Graham's figures for rubber films (§ (2)) would give a ratio of 76 per cent. In an airship it is the loss of hydrogen which immediately reduces the lift : the entrance of air is additionally disadvantageous, since it reduces the maximum lift obtainable by " topping up " or replacing lost gas.

(ii.) Accidental leakages in the apparatus and in the junction of the fabric therewith

[1] *Die angewandte Chemie in der Luftfahrt*, Münich, 1914.
[2] *L'Aérophile*, 1910, p. 156.
[3] *Advisory Committee for Aeronautics Technical Reports* : this abbreviation will be used also in references to this Committee's Reports and Memoranda.
[4] *Bureau of Standards Techn. Papers*, No. 113.

are measured as though they had occurred through the fabric. Abnormally high permeability values are liable to be ascribed to such accident.

(iii.) If the volume of the gas chamber is large, the error in adjusting the pressure to a constant value may give large errors in the volume of liquid measured: if the chamber is small, the entrance of air reduces the partial pressure of the gas and so diminishes the apparent permeability.

(iv.) Variations of temperature and of atmospheric pressure alter the volume of the gas: the temperature may be kept constant, but corrections are still required for changes in the barometric height.

§ (6) Constant-flow Methods — N.P.L. Method.—The above considerations led Rosenhain and Barr[1] to design a new type of apparatus which should be free from these defects. The diagram, *Fig.* 2, indicates the assemblage of the N.P.L. apparatus. Air from the gas-holder A is freed from carbonic acid and from moisture in the train B to F, and

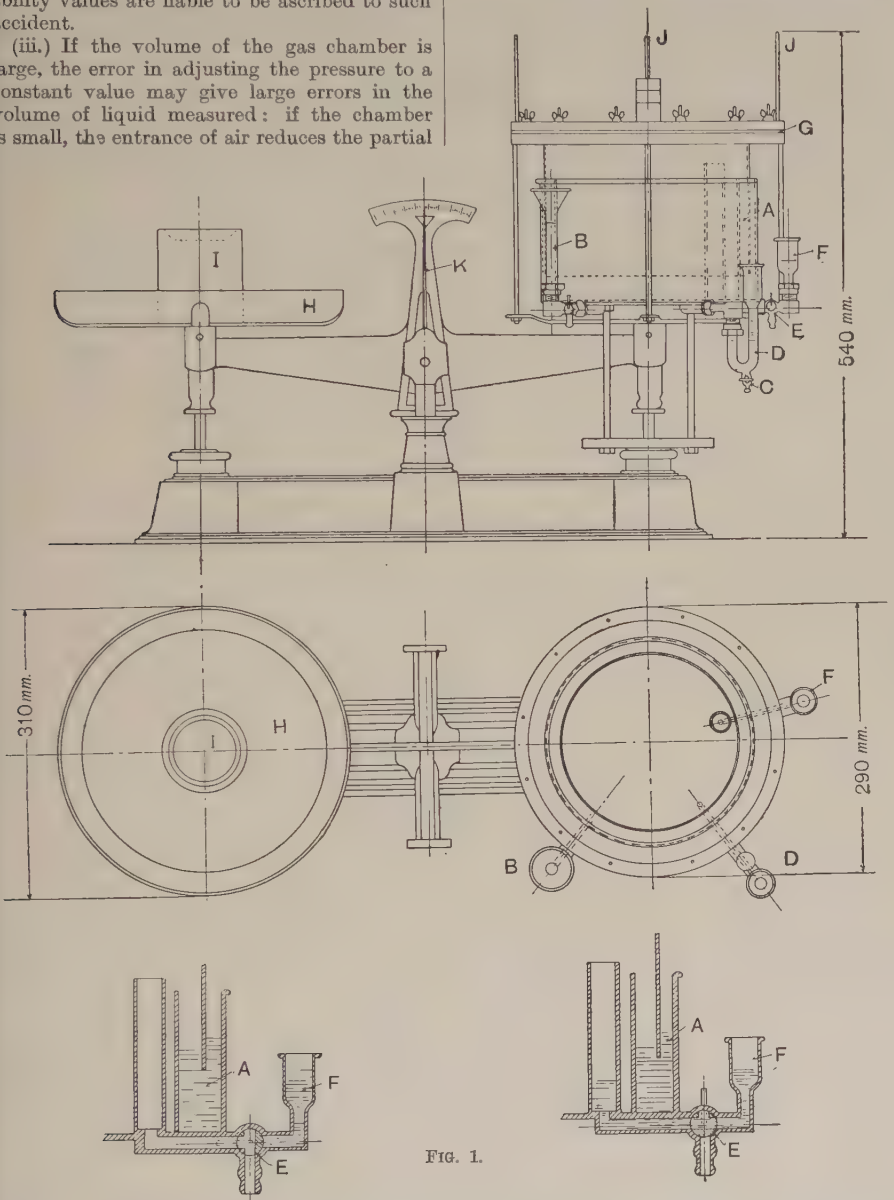

Fig. 1.

[1] *A.C.A. Techn. Rep.*, 1909–10.

flows through the upper half of the double drum G, where the fabric is clamped with an exposed area of 0·1 sq. metre: the air plus the hydrogen which has leaked through the fabric issues by the tube X and bubbles through the sulphuric acid in Q and R: after traversing the tube S, packed with copper gauze, the mixture is burned in the silica combustion tube T, containing platinised silica which is electrically heated. The water formed is absorbed in the U-tubes V and W, containing calcium chloride and pumice-sulphuric acid respectively. The copper-gauze tube S serves to damp the violence of an explosion if an exceptionally leaky fabric is being tested: such explosion is prevented from reaching the drums by the sulphuric acid seals in Q and R: the acid here is to absorb any moisture given up by the fabric. The empty tube P is to protect the drums from acid. The hydrogen is generated in K by the heating current, dried and purified in L, M, and N, and before reaching the lower drum is cooled to the working temperature in O: it escapes by the bubbler H, by means of which the excess pressure in the drum can be regulated. The difference in pressure between the hydrogen and air chambers is indicated by the manometer I. The rates of flow of air and of hydrogen are sufficiently rapid to ensure that the gas on each side remains within 0·5 per cent of pure throughout the test. The drums are enclosed in a uralite box kept at constant temperature by a heating unit, the current through which is regulated by the curvature of an invar-copper strip. The weight of water collected per hour multiplied by a constant factor gives the permeability in litres per sq. metre per twenty-four hours.

Apparatus differing from the above in a few points of detail was set up later by Heyn at the Reichsanstalt and described in *Preuss. Akad. Wiss. Berlin Ber.*, 1911, xiv. 365. The principal variation, apart from the use of glass "drums" instead of iron, was that the combustion of the hydrogen was effected in a palladium sponge tube to avoid the use of a furnace. The design of the drums was modified by Porritt (North British Rubber Co.) by the addition of a water-jacket, which simplifies the maintenance of constant temperature: he also devised a combustion tube in which the heating was effected internally by a helix of platinum wire on the surface of which combustion takes place very readily.

Similar apparatus was set up by N. Adam at Kingsnorth about 1916: for making gas-tight the junction between the fabric and the drums he used a very viscous "corn syrup" instead of the rubber washers usually employed at the N.P.L., with which a smearing of the surface with glycerin had sometimes proved necessary. At the R.N.A.S. Laboratory at Manchester rectangular water-jacketed drums were employed giving an area of ⅓ sq. meter and allowing the whole width of the roll of

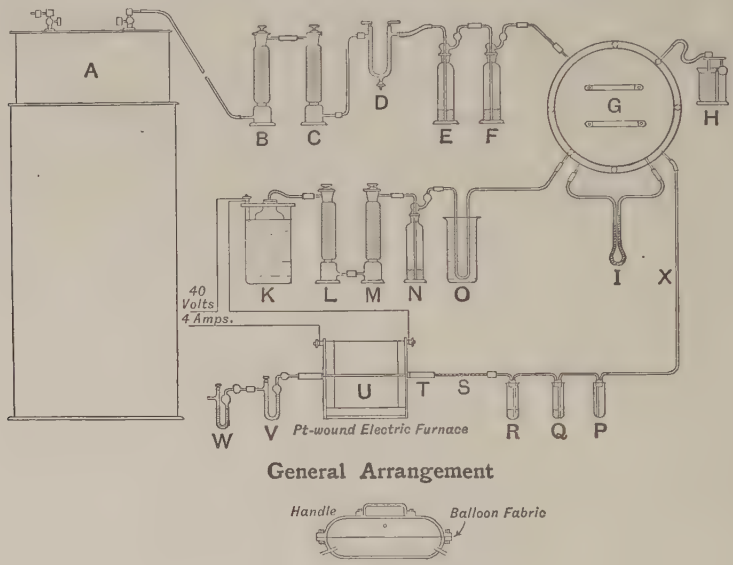

FIG. 2.

fabric to be tested: the increased area of test-piece and improvements in the combustion tube and moisture-absorption tubes allowed a test to be made in half an hour after an interval of two hours for flushing with gas and attainment of equilibrium conditions. Details of the set-up of the Kingsnorth and Manchester apparatus are given in *A.C.A. Rep. and Mem.*, 1917, No. 360.

§ (7) Interferometer Method.—The analysis of the air-hydrogen mixture issuing from the drum, which is effected by integration in the combustion method, can also be deduced from the variation of some physical property of the gas. Frenzel[1] proposed the use of the Rayleigh-Zeiss gas interferometer for this purpose. For a description of the interferometer see Haber and Lowe.[2] Frenzel employed a square drum with area of fabric 0·15 sq. metre: the rate of flow of the air stream was measured by a "precision" gasometer, and a length of capillary tube was placed so as to provide an alternative path of equal resistance when the taps leading to the interferometer were closed preparatory to an observation: this is important, since the rate of flow must be constant and accurately known. For sealing the fabric at the flanges he used water-glass solution. From the percentage of hydrogen indicated by the interferometer, multiplied by the rate of flow of the air reduced to N.T.P. and divided by the area of the fabric, the permeability was calculated.

The principle of Frenzel's method has been adopted by Edwards at the U.S. Bureau of Standards,[3] with the addition of several improvements leading to increased accuracy and rapidity in testing. In the diagram (*Fig.* 3) the fabric is shown clamped in the cell *a*, which is immersed in a thermostat *h*. Through the right-hand half of the cell dry hydrogen is passed, escaping through a bubbler *g* provided with a manometer *i*. Through the other half flows air supplied at constant pressure through the regulator *c* and dried in the bottle *e*; after leaving the cell the air is again dried in d_1 before reaching

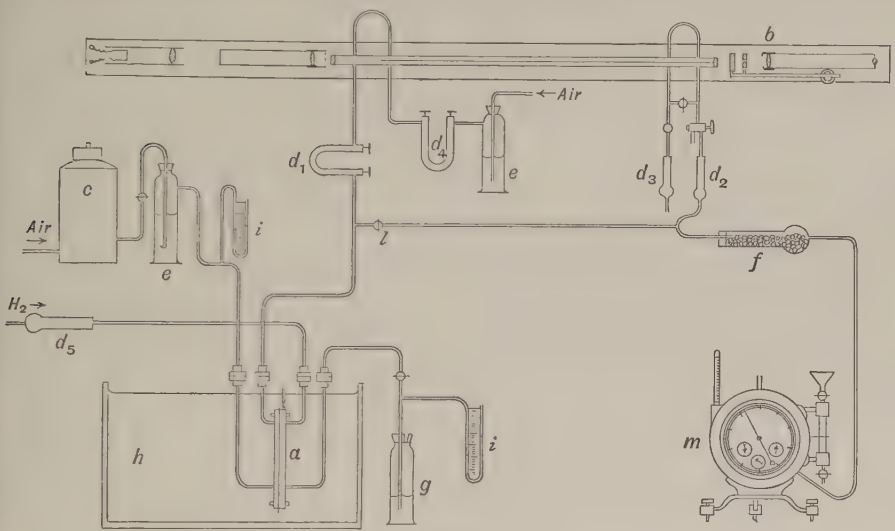

Fig. 3.

the interferometer: it leaves the interferometer through another drying tube (to prevent backward diffusion of water vapour), and before reaching the gas-meter *m* it is saturated with water vapour in *f* so as not to cause loss of water from the meter. The by-pass cock *l* allows the flow through the permeability cell to be continued while the interferometer is being read. The comparison chamber of the interferometer is filled with dry air through *e* and d_4. The standard permeability cell has a fabric area of 250 sq. cm.; the edges of the fabric are greased and the flanges which grip it have a number of fine grooves to take up the excess of grease; a wire gauze with a mesh of 3 cm. prevents the fabric from bulging into contact with the back of the air chamber, which has a depth of only some 6 mm. so that the time required for sweeping out may be short. Equilibrium

[1] *Über die Gasdurchlassigkeit der gummierten Ballonstoffe Diss.* and *Z. für Flugtechnik und Motorluftschifffahrt*, 1914, v. 264; Austerweil (*loc. cit.* p. 53) mentions that a similar apparatus was in use at St. Cyr in 1914.

[2] *Z. für angew. Chem.*, 1910, xxiii. 1393.

[3] *Technol. Paper*, 1918, No. 113.

conditions are usually established after thirty minutes.

The only other physical property of air-hydrogen mixtures which can be measured with present instruments with sufficient ease and accuracy for it to be utilised in permeability determinations is the thermal conductivity. The "Katharometer" described by Shakespear and Daynes,[1] which depends on this property, has been used in only a few investigations by the constant-flow method: its application has been almost exclusively to block by the working current of the bridge. One of the cavities contains pure air and is sealed: the other communicates by three capillary openings with the air chamber of the permeameter. The presence of hydrogen in this air increases the thermal conductivity and so causes the temperature and resistance of the exposed coil to fall; the bridge is thus thrown out of balance by an amount depending on the concentration of the hydrogen. In the instrument as made by the Cambridge Scientific Instrument Co., illustrated in *Fig.* 4,

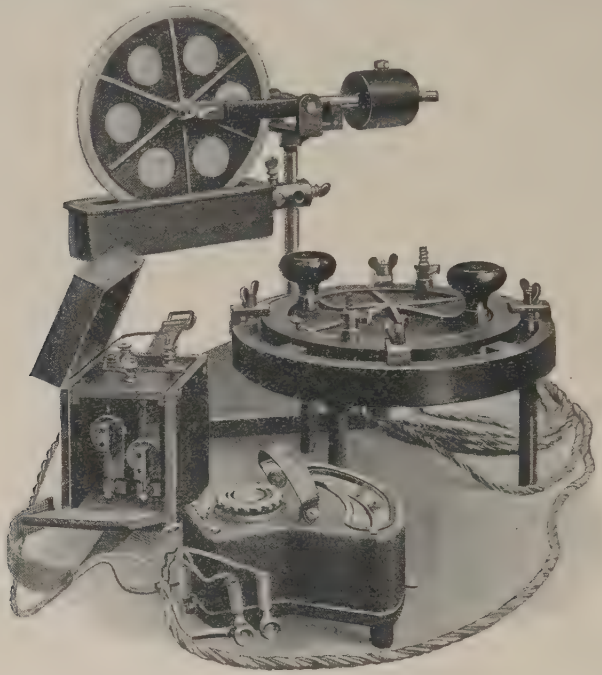

FIG. 4.

the "constant-volume" method, which forms the subject of the next section.

§ (8) CONSTANT-VOLUME METHOD.—For the measurement of permeability by a constant-volume method, the devices for indicating the concentration of hydrogen in the air chamber must not necessitate the use of large volumes if the apparatus is to operate rapidly. The necessary sensitivity and small working volume are secured in the Shakespear apparatus[2] by the use of a "Katharometer." This consists essentially of a copper block into cavities in which are inserted coils of fine platinum wire, which form two arms of a Wheatstone bridge and have their temperature raised some 15° C. above that of the galvanometer scale can be read to 0·02 per cent of hydrogen, and the volume of the cavity in which is the exposed coil is only about 0·5 c.c. The permeability cell accommodates a specimen of area 100 sq. cm.: the air chamber, which is the lower, is 6 mm. deep, and is provided with concentric rings to prevent sagging of the fabric, and in the centre of it is screwed the copper block of the "Katharometer." A continuous current of hydrogen flows over the upper face of the fabric. During the time required for flushing, air is passed through the lower chamber *via* holes bored horizontally in the base. The tubes for supply and outlet of air are then removed and the holes closed by plugs ground to fit, and the rate of increase of the concentration of hydrogen in the enclosed air is observed

[1] *Roy. Soc. Proc.*, 1920, xcvii. 273.
[2] *A.C.A. Rep. and Mem.*, 1917, Nos. 317 and 516.

on the galvanometer. Owing to the small size of test piece and the shallowness of the hydrogen chamber the flushing requires only about ten minutes: with a fabric showing a normal permeability the test is completed in about another twenty minutes. The temperature is given by a thermometer inserted into the katharometer block. Owing to the lack of a water-jacket, adjustment to a given temperature may take much longer than the actual test, since the apparatus is not designed to allow immersion in a water thermostat. Knowing the volume of the air chamber and the area of the fabric, the permeability can be calculated from the galvanometer observations. A small correction is necessary for the effect of the partial pressure of the hydrogen in the air on the rate of leakage; the indicated volume of hydrogen has also to be reduced from the temperature of the experiment to 0° C., but no correction for barometric pressure is required. If the katharometer was calibrated at a temperature other than that of the test a further correction to the reading of the galvanometer must be made; also if the galvanometer scale is graduated, as is usual, in percentages of hydrogen *in the mixture*, the figure must be converted to percentage of hydrogen *added* to air.

The writer has shown[1] that the chief limitation to the accuracy of this method, as compared with constant-flow methods, is the uncertainty in the determination of the volume of the air chamber. The working volume is not that found by replacing the fabric by a flat plate and measuring the volume of water or of a gas (preferably the latter) so enclosed, but is less than this by an amount determined by the sag of the fabric. The decrease in volume varies with the amount of the excess pressure on the hydrogen side, and also with the nature of the fabric under test. Thus with an instrument in which the concentric rings supporting the fabric were 1 cm. apart, a single-ply fabric sagged so as to decrease the volume of 65 c.c. by 3·1 c.c., a two-ply by 2·4 c.c., and a three-ply by 1·5 c.c. when the pressure difference was 30 mm. of water. The error due to these causes may be reduced by lowering the pressure difference; in the most recent specification of the B.E.S.A. the difference is required to be equal to 2 mm. of water instead of 30 mm. as heretofore. With this pressure the variability of the extension of the fabric will introduce little error.

The Shakespear permeameter provides the most convenient and rapid means of determining permeability which has yet been devised. If the calibration of the katharometer is precise and the volume of the air-chamber is accurately known, the results will be as reliable as those given by a constant-flow method. For work at a constant temperature the apparatus might be modified in detail either by so designing it that it could be immersed in a liquid thermostat or by providing water-jackets to the two halves of the permeability cell. The rings supporting the fabric might with advantage be more numerous so as to reduce the error due to bulging of the fabric.

§ (9) Effect of Experimental Conditions on the Results of Permeability Determinations.—There are certain considerations which affect the accuracy of the results obtained with any of the various types of apparatus described in the preceding section. In addition to those discussed below each method of determination requires precautions incidental to that method, such as accuracy in the calibration of an interferometer or katharometer: these are outside the scope of this article.

(i.) *Preparation of Specimen.*—The smaller the area of the fabric under test the less is the allowable error in the delimitation of that area. In most apparatus the inner edge of the flange of the drum is assumed to isolate the enclosed fabric. For such large areas as are used in the N.P.L. and Manchester drums the error is probably unimportant with most classes of fabric. It has, however, been observed,[2] that in certain classes of rubbered fabric serious leakage of hydrogen may occur between two layers of rubber separated by a layer of the textile: this is most obvious when one of the rubber layers is merely a thin facing of 10-30 gm. per sq. m. on that side of the fabric which is to be exposed to hydrogen, the main gas-holding layer being totally separated from it by the thickness of the cotton threads. In such cases, the flange does not define the area which is exposed to the gas, and the true permeability could only be obtained directly with an infinitely large area. Daynes (*loc. cit.*) has measured the rate of lateral diffusion along the textile for seven balloon fabrics of different construction or manufacture, and found values of 0·0005 to 0·0010 for the "penetrability" or diffusion constant, defined as the number of c.c. of hydrogen per second which cross a section of the textile 1 cm. long for unit concentration-gradient normal to that section: by concentration is understood the ratio of partial pressure of the hydrogen to the total gas pressure, so that unit gradient of concentration will occur if the textile is exposed to pure air at 1 cm. from the section where it is exposed to pure hydrogen. From a mathematical analysis of the problem, with certain plausible assumptions, he concludes that if

[1] *A.C.A. Rep. and Mem.*, 1908, No. 504.

[2] Barr, *A.C.A. Rep. and Mem.*, 1917, No. 313; Shakespear and Daynes, *ibid.*, 1917, No. 367, and 1918, No. 435.

the cut edge of a two-ply fabric is not sealed the loss of gas between the two layers of rubber in the worst case—that in which the two are equally permeable—may cause the apparent permeability to be some 20 per cent lower than its true value, even with a test area of 1000 sq. cm. If the cut edge is at a distance of 1 cm. from the inside of the flange and is sealed by some gas-tight material which extends over that 1 cm., the apparent permeability may be increased in the worst case of a three-ply balloon fabric—that in which the middle layer of rubber is good and the two outside layers are very permeable—by some 38 per cent for a 100 sq. cm. circle owing to the extension of the effective area by diffusion along the two textile plies on each side of the main rubber layer. For a test piece of area 1000 sq. cm. the error would be about 11 per cent, but both of these estimates would be increased if the width of border covered by the sealing mixture were greater than 1 cm. These figures for maximum error do not affect the reproducibility of the results on a given apparatus. The precision of testing may amount to 1 per cent, but in such extreme cases, tests on pieces of different areas would give different results.[1] The differences could only be reconciled by measuring the permeabilities of the separate layers of rubber and the coefficients of diffusion along the textile and applying a correction for the edge effect.

Present practice in the manufacture of balloon fabrics tends in the direction of accumulating as much of the proofing as is convenient into one layer, leaving only small margins of weight for the rubber required for sticking extra plies of textile to it, or for providing facings. Thus a two-ply fabric will have a main rubber layer between plies weighing some 90-100 gm. per sq. m., and having a permeability of the order of 10 lits. per sq. m. per day, and on the gas face either no rubber at all or only a coating of 10-30 gm. per sq. m. For such a facing the minimum permeability observed by Daynes was 160 times that of the main layer. Assuming values of 1000 lits. per sq. m. per day for the facing and ·001 cm.-sec. units for the lateral diffusion constant, the error in permeability determination with a 100 sq. cm. drum would amount, on the assumptions previously made, to some 7 per cent if the edge were not sealed. Two-ply fabrics must, therefore, always have their cut edges sealed, and since the sealing mixture can obtain access to one surface of the main layer, it may be used also to delimit the area under test by means of a covered border. This is the method adopted in the normal use of the Shakespear permeameter: the fabric is clamped between two equal accurately turned metal discs which are mounted co-axially, and the whole is dipped in a melted mixture of beeswax and vaseline. On cooling, the semi-solid grease serves to define the exposed area and to ensure gas-tightness at the junctions between the fabric and the flanges of the drums.

With a three-ply, or doubly faced two-ply, fabric consisting of two thin rubber layers separated by textile from the main rubber proofing, this method of procedure will, as shown above, give large errors even when the disc has an area of 1000 sq. cm. Such fabrics may be tested with unsealed edges if the area is large, *e.g.* on the N.P.L. drums the error would be less than 2 per cent. Using a 100 sq. cm. permeameter the results would be 7 per cent low; if this size is to be used it becomes necessary, as suggested by the writer (*loc. cit.*), to remove the coating of rubber on the gas side mechanically before applying the sealing mixture. This may be done with sufficient accuracy while the fabric is clamped between the discs preparatory to dipping.

(ii.) *Effect of Humidity.*—Various isolated observations have pointed to the probability of the permeability being affected by the hygrometric state of the gases with which rubber is in contact. Payen found in 1893 that water was absorbed by rubber to the extent of ·04 per cent on long standing. Another observer[2] noticed that a rubber tube full of carbon dioxide, which under normal conditions collapsed in twelve hours owing to the permeation of the gas through the rubber, did not collapse in a month when the system was dry and was kept in a desiccator, although practically all the carbon dioxide had then escaped: this indicates that the permeabilities by this gas and by air are differently affected by moisture. When the N.P.L. apparatus was originally designed, a condition of dryness was selected owing to the convenience of removing as much moisture as possible from the air stream by bubbling through sulphuric acid before it became mixed with hydrogen; only the small quantity of water taken up from the fabric had then to be removed before combustion. The hydrogen and air currents used to be left running overnight to establish steady conditions before beginning the test. With the use of smaller drums and the development of more rapid methods of testing, the drying of the fabric necessitated a delay. Shakespear[3] accordingly investigated the effect of drying on the permeability of two

[1] Edwards and Pickering (*Bureau of Standards Sci. Paper*, 1920, No. 387) give the results of tests on a two-ply fabric having rubber facings on both sides—which is thus similar to the three-ply material above mentioned—showing that when the exposed area of a 130 cm.² test piece was 100 cm.² the apparent permeability was 11·8 lits., while with an exposed area of 70 cm.² it was 16·6 lits.

[2] Rodt, *Chem. Ztg.*, 1914, xxxviii. 1249.

[3] *A.C.A. Rep. and Mem.*, 1917, No. 317.

fabrics, and found that when the samples were tested in the ordinary air-dry state the observed rates of permeation were in one case 4 per cent and in another 6·6 per cent lower than when they were exposed to dried gases for three or four hours. This result was confirmed at the N.P.L.[1] on the Shakespear apparatus. A reproducible difference of ·5 per cent was found between the permeabilities indicated for a "10 litre" fabric after twelve hours' contact of the fabric with gases which had been respectively bubbled through concentrated sulphuric acid and through water at the temperature of the apparatus, *i.e.* about 18° C. An effect of the same order is noted by Edwards.[2] When the gases were at 65 per cent relative humidity the observed leakage at 25° C. was 4 to 5 per cent lower than when they were dried by sulphuric acid. The time of contact is not stated, but it is mentioned that the dry gases still took up some moisture from the fabric after several hours' passage. The water vapour in two-thirds saturated hydrogen at 25° C. or in saturated gas at 18° C. reduces the partial pressure of the gas by some 2 per cent, so that the desiccation is only responsible for a 2 to 3 per cent increase of permeability both in Edwards' and in the N.P.L. experiments. The Bureau of Standards accordingly recommends the use of dried gases, considering the gain in accuracy obtainable by regulating the humidity not worth the extra complication in procedure. The latest specifications of the British Engineering Standards Association, however, require the gases to be brought to 65 per cent relative humidity by bubbling them through dilute sulphuric acid (35·5 per cent acid, D_4^{15} 1·268) at the temperature of the drums.

This procedure is adopted in the light of more complete experiments reported by Ritchie,[3] which show—

(*a*) That the effect of partial saturation with moisture is only of the above order with fabrics of moderate permeability, but that with fabrics leaking 25 or more lits. per sq. m. per day the decrease in rate of leak after twelve hours' contact with the saturated gases may amount to 38 per cent, and

(*b*) That saturation is not complete, with the rates of flow and dimensions used by him, after twelve hours, but causes decreases in leakage after fifty hours, which may amount to 20 per cent or so even for fabrics showing a permeability when dry of 10 lits. per sq. m. per day.

Ritchie himself concludes that it is only for fabrics of high permeability that the hygrometric state is of importance in routine testing, and that the use of dried gases is permissible since the large variations found by him only occur when the fabric is almost fully saturated, a condition which is not liable to occur in ordinary laboratory tests.

(iii.) *Effect of Residual Solvent.*—In addition to moisture, which is a normal constituent of a proofed fabric, certain classes of airship fabric may also contain small quantities of the solvent used in compounding the rubber dough used for "spreading" the proofing on the fabric. Although the subsequent heating, which occurs after each passage through the "spreader" in order to allow the material to be wound on to rollers, and the final "curing" of the mixture in the vulcanising chamber are supposed to eliminate all the solvent, it is obviously possible that small quantities may remain in a heavily proofed fabric of recent manufacture: in fact the solvent can often be smelled. Ritchie (*loc. cit.*) notes that errors due to solvent have occurred in the testing of some types of skin-lined fabric (rubbered fabric to which goldbeaters' skin has been stuck by means of rubber cement) and of seamed test pieces, in neither of which cases, of course, had the material been heated after the application of the cement. Apart from such instances, Edwards (*loc. cit.*) mentions that fabrics of one composition only among many tested at the Bureau of Standards had been shown to occasion the possibility of error from this source. It may be remarked that the evolution of solvent vapour would cause the apparent permeability to be too high when the hydrogen is determined by combustion, and too low when the gaseous mixture is analysed by means of the interferometer or katharometer. The use of sulphuric acid as the agent for drying the gaseous mixture which leaves the drums is some safeguard against errors of this nature, since the strong acid is an absorbent for aromatic hydrocarbons which constitute the usual "solvent naphtha" employed. Only the paraffinoid hydrocarbons are then to be feared, and these are of comparatively infrequent occurrence in the proofing. It is in fact found that the first acid tube in the N.P.L. apparatus (Q of *Fig.* 2) soon becomes discoloured in the ordinary use of the installation, owing to the absorption of vapours, and requires frequent renewal. In any of the methods for permeability determination, errors due to solvent may be eliminated by running a blank test with air on both sides of the fabric before and after the test proper and applying a mean correction. In practice this would only be done if the fabric had a pronounced odour of solvent.

(iv.) *Effect of Temperature.*—Graham noticed that rubber films increase in permeability with rise in temperature. That the same

[1] Barr, *A.C.A. Rep. and Mem.*, 1917–18, No. 504.
[2] *Bureau of Standards Techn. Paper*, No. 113.
[3] *A.C.A. Rep. and Mem.*, 1917, No. 360.

applies to balloon fabrics was observed by Rosenhain and Barr,[1] and measurements of the temperature coefficients have since been made by several workers. Since the permeability of rubber has been shown to be a function of two physical processes having different temperature coefficients (in § (3)), it is hardly to be expected that there should exist any simple law connecting temperature and permeability. That there is, however, at least a good approximation to a logarithmic relationship is shown by the subjoined diagram (*Fig.* 5). Results obtained by

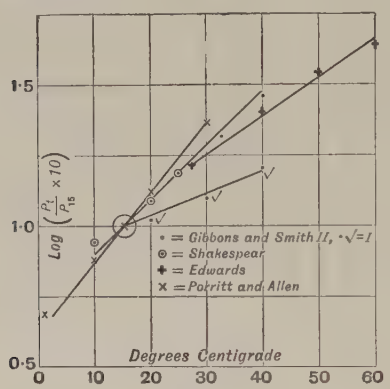

FIG. 5.

Gibbons and Smith [2] with two fabrics I. and II. having respectively 1·65 and 5·51 oz. of rubber per sq. yard, by Porritt and Allen,[3] by Shakespear,[4] and by Edwards,[5] have been reduced to a common permeability of 10 lits. per sq. m. per day at 15°·5 C., and the logarithms of these reduced permeabilities plotted against temperature. It will be seen that the points for Gibbons and Smith's heavier proofing and for Shakespear's fabric lie nearly on the same straight line, while the divergences from straight lines in the other cases are probably within the limits of error of the experiments. Further, it may be remarked that the highest coefficient is given by the fabric used by Porritt and Allen, for which the permeability at 15°·5 C. was 4·7 lits., and the lowest by Gibbons and Smith's lighter fabric, which had at that temperature a permeability of 50·6 lits. per sq. m. per day. The other fabrics had permeabilities at 15°·5 C. in the neighbourhood of 10 lits. Hence it appears to be a rough rule for rubbered fabrics that the better the proofing the higher is the temperature coefficient.

[1] *A.C.A. Techn. Rep.*, 1910–11.
[2] *First Ann. Rep. of N.A.C.A.*, Washington, 1915.
[3] *A.C.A. Rep. and Mem.*, 1917, No. 513.
[4] *Ibid.*, 1918, No. 504.
[5] *Bureau of Standards Techn. Papers*, 1918, No. 113.

This is in accordance with the usual view that high permeabilities are the result of defective manufacture and are due to ordinary diffusion or effusion through minute holes or passages: the temperature coefficients of these processes are much lower than that of permeability or diffusion *in* rubber.

As mentioned above (p. 138), a logarithmic relation was found also by Dewar for rubber films. The only results which are in contradiction with all others are those of Frenzel,[6] who found a constant temperature coefficient for the continental fabrics used by him. The data available are insufficient to deny the possibility of his results having been accurate.

(v.) *Effect of Pressure.*—The pressure prevailing in the test drums influences the apparent permeability in two ways. If the pressure is the same, or differs by a constant amount, on the air and hydrogen sides of the fabric, the mass leakage may be expected to be proportional to the pressure, since the solubility of hydrogen in rubber was proved by Kayser to be proportional to the pressure, *i.e.* to the concentration of the gas. The observed rate of permeation should, therefore, vary with the barometric pressure prevailing. This has not actually been noticed, since the normal variations in atmospheric pressure do not exceed some ±2 per cent, which is nearly the limit of accuracy of the best determinations.

It has, however, been proved fairly conclusively that the permeability is proportional to the partial pressure of the hydrogen when this is varied by the admixture with it of another gas.[7] The practice has accordingly been adopted by most workers of reducing the permeability observed at a barometric pressure p to that at the standard pressure of 760 mm. of mercury by multiplying it by $760/p$.

Several investigators have occupied themselves with the problem of the effect of the difference of pressure between the two sides of the fabric. The working pressure which is necessary in a non-rigid airship in order to preserve its form and to support the load carried is of the order of 30 mm. of water in excess of the external pressure: in a spherical balloon of diameter 10 metres with filling pipe open, the excess pressure due simply to the height of the hydrogen column is 13 mm. of water at the top. Since the leakage of gas from a balloon or airship used to be considered as due to actual porosity of the proofing, and would therefore be expected to vary with the pressure difference, it became usual to specify that an excess pressure of 30 mm. of water

[6] *Über die Gasdurchlassigkeit der Ballonstoffe*, 1914.
[7] Barr and Thomas, *A.C.A. Techn. Rep.*, 1912; Edwards and Pickering. *Chem. and Met. Eng.*, 1920, xxiii. 19.

should be maintained during the permeability test. In so far as fabrics of high permeability are concerned, in which part of the leakage occurring is possibly due to actual effusion or transpiration through minute pores or capillary passages, and for tests on seams in which such effusion is always liable to occur along the cut edge of the fabric, the retention of this figure for the excess pressure is advisable. But with rubbered fabrics giving permeabilities of less than 10 lits. per sq. m. per day the porosity must account for only a small fraction of the total leakage unless the pores are both exceedingly small and exceedingly numerous. Thus Ritchie [1] calculates that effusion through a single hole 0·01 cm. in diameter would give an apparent permeability, on a 1000 sq. cm. sample, of some 30 lits. per sq. m. per day, and that transpiration through tubes ·01 cm. long (=thickness of rubber layer) and 0·001 cm. in diameter would give a leakage corresponding with 70 lits. per sq. m. per day if the tubes occurred so infrequently as one per sq. cm. Actually, the latter diameter being only rather less than sixty times the mean free path of hydrogen at atmospheric pressure, the calculated leak needs to be increased in order to take account of the "slip" occurring at the walls of the supposed tubes (cf. Kundt and Warburg's experiments on the flow of gases through tubes when the mean free path is no longer a small fraction of the diameter of the tube). For tubes of smaller diameter the effects of viscosity eventually become negligible in comparison with what Knudsen [2] calls "molecular flow," which for a given excess pressure varies as $r^3/\sqrt{\rho}$ instead of as r^4/η as in viscous flow (r=radius of tube, ρ=density of gas, η=viscosity of gas).

No evidence has ever been produced which demonstrates the existence of any porosity in good balloon fabrics. Different workers have obtained very variable figures for the increase in permeability occurring when the excess pressure is raised. Thus, for two-ply fabrics over the range 10 mm. to 60 mm. water excess pressure Frenzel (*loc. cit.*) found increases of the order of 30 per cent, Ritchie [3] 6 per cent, and Edwards and Pickering (*loc. cit.*) about 6 per cent. The change in partial pressure of the hydrogen accounts for only 0·5 per cent of the increase in permeability; the variable remainder is to be ascribed to the different extensions of the test pieces. The extension and consequent thinning of the rubber is checked by two causes: of these one is the result of the support afforded to the rubber membrane by the plies of textile on which it is spread, the textile stretching very much less than rubber would do after a given small pressure difference has been exceeded. In many designs of permeameter the bulging of the fabric is reduced by means of projections from the drum or by wide-meshed wire gauze. The tension produced in the fabric by a given excess pressure will consequently vary with the dimensions and construction of the permeameter. The larger effect found by Frenzel than by Edwards is presumably, therefore, to be correlated with the fact that his fabric was unsupported over a square of 38 cm. side, while Edwards used a gauze support with a 3 cm. mesh. Experiments on the variation of permeability with pressure difference must therefore be interpreted with some caution: they are of little practical value, apart from the study of the particular apparatus used, unless accompanied by determinations of extension, which can be most readily made by allowing the fabric to bulge freely in a circular drum and measuring the height of the nearly spherical cap produced. The conditions occurring in an airship where a small excess pressure produces a considerable tension are not so readily reproduced: the true pressure effect, that on the viscous flow of the gas through pores, requires to be observed separately by some such means as that suggested, but the effect of the extension produced in the envelope must be obtained by producing the required change in dimensions before clamping the test piece in the permeameter. No tests of this nature appear to have been made on rubbered fabric, though they are important for airship practice.

(vi.) *Purity and Rate of Flow of Gases.*—It is obvious that if the hydrogen contains air or other impurity the observed permeability will be too low. It has been shown (see preceding section) that the permeability is proportional to the partial pressure of the hydrogen: hence, if the gas contains any impurity the presence of which has no effect on the subsequent analysis of the air-hydrogen mixture produced by the leakage through the fabric, the results obtained may be corrected by multiplying by the necessary factor. In the N.P.L. apparatus the hydrogen is prepared by electrolysis on the spot, and hence contains practically no impurity except some 0·25 per cent of oxygen: within the limits of accuracy of the apparatus this amount is negligible. Hydrogen obtained from cylinders may contain carbon monoxide and nitrogen: the former constituent is objectionable when the interferometer is to be used in estimating the diffused hydrogen, since its refractive index is considerably higher than that of air, and the concentration of the hydrogen deduced from the reading of the instrument would be too low if carbon mon-

[1] *R. and M. of A.C.A.*, 1919, No. 584.
[2] *Ann. d. Phys.*, 1909, xxv. 75.
[3] *R. and M. of A.C.A.*, 1917, No. 360.

oxide were present. In thermal conductivity it does not differ much from air, and by a combustion method it would not form any water to be absorbed in the drying tubes. Impurities other than hydrogen in the air used are either without effect or can readily be eliminated: in order to avoid the presence of the former gas the air is preferably drawn from outside the building.

The speeds of the hydrogen and air currents passing over the fabric should be such that the amount of either gas leaking through the proofing does not sensibly affect the purity, otherwise corrections become necessary for the fact that the difference in partial pressure is no longer 100 per cent. This condition is satisfied if the concentration of hydrogen in the air or of air in the hydrogen is not more than 0·5 per cent by volume, since none of the methods used aims at any higher accuracy than about 1 per cent. The larger the test piece, consequently, the more rapid must be the rates of flow: for an exposed area of 0·1 sq. m. of a fabric leaking 20 lits. of hydrogen per sq. m. per day, the velocity of air required is some 8 lits. per hour; the hydrogen stream does not need to be more than 1·5 to 2 lits. per hour. If it is inconvenient or, as in Shakespear's constant volume method, impracticable to keep the concentration of hydrogen in the air to so low a figure, a correction must be made. It may be pointed out that, in a constant flow method, if the issuing mixture contains 2 per cent of hydrogen the correction is only 1 per cent, since this is the average concentration of hydrogen in the air inside the drum. It is assumed, as appears reasonable theoretically and from some experiments by Edwards, that turbulence of the currents is not appreciably more effective than is free diffusion in removing the gas which has permeated the fabric from the immediate vicinity of the surface of the proofing.

(vii.) *Equilibrium Period and Duration of Test.*—As was mentioned above (§ (9) (i.)), the streams of hydrogen and air in the N.P.L. apparatus used to be left running overnight before beginning a test: this was largely because of the small capacity of the electrolytic hydrogen generators relative to the volume of the rest of the apparatus. When it became necessary to carry out more than one set of tests per day the air was removed from the lower drum by the use of compressed hydrogen, which allowed a more rapid sweeping out. Ritchie (*loc. cit.*) gives details of tests on drums having dimensions similar to those of the N.P.L. apparatus but shallower, the volume of each half of the drum being some 2·5 lits., which show that when the hydrogen and air are passed in at rates of about 15 lits. per hour, the air is all expelled from the hydrogen side and a uniform composition obtained in the air side after about fifty minutes. The much smaller volume of hydrogen chamber in the Shakespear apparatus (50 c.c. or so) can be swept out in ten minutes.

Edwards[1] gives results for the rate of absorption of hydrogen by rubbered fabric exposed to the gas on both sides, which point to the conclusion that the rubber is not saturated under these conditions until it has been in contact with hydrogen for sixty to ninety minutes, but Shakespear mentions tests[2] which indicate that a correct figure for the permeability was obtained in two cases within ten minutes of starting the hydrogen stream. An equilibrium period of from half an hour to an hour is now generally recognised as being sufficient after the hydrogen side of the apparatus has been flushed. Cases are recorded, however, in which certain balloon fabrics have shown curious variations in permeability over periods of a few days or even hours. Thus Edwards (*loc. cit.*) mentions the following: (1) A steady decrease from 15·1 lits. to 14·4 lits. during four successive days; (2) a decrease from 21·4 lits. to 19·2 lits. in 2½ hours; (3) a decrease from 18·9 to 14·5 lits. in 4 hours—another test piece from the same fabric four months later showing a decrease during 2½ hours test from 17·2 lits. to 12 lits. Ritchie cites a case (4) where duplicate determinations on the same samples gave 5·5 lits. and 7·45 lits. at the first test, and 9·9 lits. and 10·1 lits. when re-tested four days later. Variations of the order of a few per cent have been noticed at the N.P.L. when tests have occasionally been prolonged over a whole week, but it has usually been possible to ascribe them to accidental inconstancy of flow of air or gas, to defective temperature control, to the development of leak in the apparatus, or some such cause. The four instances given above are, however, vouched for by the respective authors. It may further be remarked that the decreases found by Edwards and the increases noted by Ritchie are both, owing to the different methods of analysis used by the two experimenters, in the opposite direction to that which would be caused by gradual removal of residual solvent from the proofing. Ritchie suggests that changes such as those known to occur in "after vulcanisation" are responsible for the variations in permeability, the latter property being capable of indicating small differences in the structure of the film which are at present detectable by no other chemical or physical method of examination. The higher temperature of test (25° C.) used by Edwards would tend to make the phenomena more readily noticeable: indeed, he remarks

[1] *Bureau of Standards Techn. Paper*, No. 113.
[2] *A.C.A. Rep. and Mem.*, 1917, No. 317.

that heating the samples to 50° C. or 70° C. generally causes a decrease in permeability.

(viii.) *Methods of Testing the Permeability of Seams and of Envelopes in Service.*—The proofed material used in the construction of balloons is usually manufactured in rolls of a width not greater than about 1 metre. It is obvious, therefore, that there must be over 1 metre length of seam to every square metre of fabric. Owing to the design of the envelope the ratio is more nearly of the order of 3 metres of seam per square metre in certain balloons. Hence the leakage at the seams may form a serious item in the gas consumption, if the normal permeability of the fabric is exceeded in the seams. Without entering into details of the methods employed in seaming, it may be explained that the cut edges of the fabric are overlapped, say, 2 cm., stuck together with rubber solution, and sewn with a double row of stitches some 1 cm. apart, and the free edge and stitch holes are solutioned and covered over with "tape" consisting of a width of some 4 cm. of single-ply fabric, cut on the bias and provided with a facing of rubber. The stitching is required although the stuck seams are initially as strong as the remainder of the fabric, since on exposure there is a possibility of the adhesion failing unless the work has all been very carefully performed. Obviously the rows of stitches provide areas of egress for the hydrogen, and the tapes are intended to reduce the leakage due to this cause. From the observations mentioned in § (9) (i.) it is clear that considerable leakage might also occur laterally along the textile between the various layers of rubber, except with a fabric which has gas-tight rubber coatings both on the inside and outside faces, an arrangement which is unusual for other reasons: if the tape performed its function properly this leakage would be inhibited by the fact that the tape extends beyond the cut edge of the fabric and is stuck to the subjacent material. It is consequently important to examine the behaviour of a complete seam.

The usual methods of permeability determination have been applied to the investigation of seams by comparing the leakage observed for a test piece of ordinary material with that given by a piece which includes a seam or, if the drums used are large, as at the N.P.L., by a specially made piece in which several seams or a circular seam have been made so as to increase the length tested, relative to the area of sample. This procedure was sufficient to show the additional leakage which the presence of seams of different construction would cause in an envelope, but improvements could only be made by methods of "trial and error."

A valuable aid to the study of seam leakage was devised by Shakespear,[1] who applied the principle of his katharometer (see § (8)) to this purpose by providing it with a projecting ring of about 7 mm. diameter and 1 mm. thickness which could be applied to the fabric, the other side of which was in contact with hydrogen. The small volume of air so enclosed, not much more than 0·5 c.c. in all, becomes contaminated with hydrogen leaking through the area examined, and the rate of contamination is observed by the deflection of the galvanometer of the bridge circuit. Since the joint between the metal ring and the fabric is by no means gas-tight, the concentration of hydrogen in the katharometer is not allowed to rise above 0·05 per cent, at which value the effect of edge leakage is in general unimportant. The requisite sensitivity is obtained by the use of a reflecting galvanometer instead of the portable type preferred for the ordinary permeameter. The effects of edge leakage being of roughly the same order for different parts of the same fabric surface, the rate of deflection of the galvanometer is proportional to the permeability at any part tested: the absolute value of the permeability is obtained to the degree of approximation necessary by making a number of such tests on a piece of the same fabric which has been tested in the ordinary way and deducing the requisite factor. By the aid of this instrument the quantities of gas escaping from areas of 40 sq. mm. can be determined, so that the location of leaks is sharp. Shakespear was able to show that even when the tape itself had a permeability no greater than that of the fabric very large leakages frequently occurred in seams made by balloon constructors owing to imperfect solutioning of the tape to the fabric: the leakage in such cases was shown to be due to diffusion along the textile either between the main layer of rubber and the thin facing or, where no facing was used, between the rubber layers of the balloon fabric and of the tape. The former cause of loss of gas could be avoided by omitting the facing or by making it heavy enough to be reasonably gas-tight, the latter by requiring that for the first applications of rubber solution to the textile surface the solution should be of low viscosity and should be well rubbed in so as to penetrate through the cotton. *Fig.* 6, taken from Shakespear's paper, illustrates the distribution of the leakage, S.B. 1 for a fairly good tape improperly solutioned, S.B. 14 for a bad tape fairly well solutioned. The small circles represent the imprints made by the nozzle of the exploring katharometer, the figures inscribed being the permeabilities there indicated, calculated as per sq. m. per day. The dotted lines repre-

[1] *A.C.A. Rep. and Mem.*, 1917, No. 367, and 1918, No. 435.

sent the lines of stitching, the full lines next to them the positions of the cut edges, that to the left being the concealed inner edge of the right-hand panel; the outer full lines are the edges of the tape.

A simpler but less sensitive test has been used by Ritchie,[1] which consists in clamping a sample over a cylindrical brass vessel having an inside diameter of 11·5 cm. and forcing

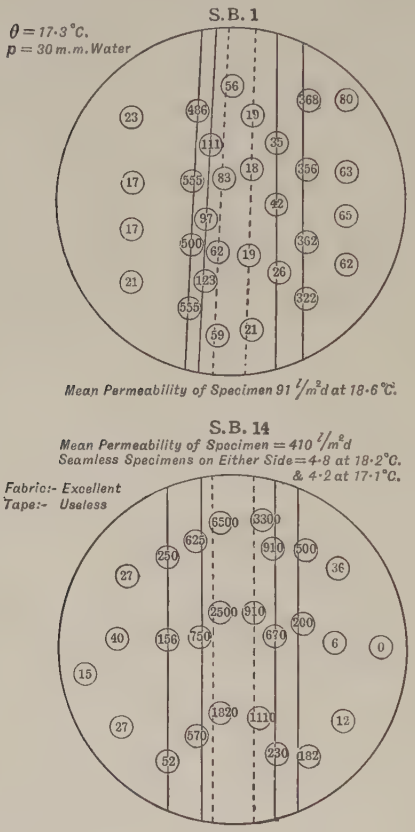
S.B. 1
θ = 17·3°C.
p = 30 m.m. Water
Mean Permeability of Specimen 91 l/m²d at 18·6°C.
S.B. 14
Mean Permeability of Specimen = 410 l/m²d
Seamless Specimens on Either Side = 4·8 at 18·2°C.
& 4·2 at 17·1°C.
Fabric:- Excellent
Tape:- Useless

FIG. 6.

hydrogen into the enclosure up to a pressure of 20-40 cm. of mercury. This procedure puts the fabric under a tension which can be calculated from the height of bulge and the observed pressure: the pressure is adjusted until the calculated tension is 100 or 200 kg. per metre, the latter figure approximating to the average tension in airships of the S.S. type. The surface of the fabric is painted over with soap solution, and from the positions and sizes of the bubbles produced in a given time the leaks can be located and their relative magnitudes compared. Very small leaks can be detected in this way, and the application of higher pressures rarely reveals any more. The essential difference between this method and Shakespear's is that the leaks which are magnified by increased excess pressure so as to become visible must be such as occur not by true permeation through rubber but by transpiration through capillary passages: permeation would be magnified only in the ratio 96/76 or 116/76, transpiration is increased in the ratio 272/3 or 544/3 over that occurring in the standard test under a pressure of 3 cm. of water. Thus in the sample S.B. 1 of *Fig.* 6 Ritchie's test would probably indicate the leakage at the edges of the tape only, but since the general quality of the tape can be separately examined this is not a very serious defect for the purpose in hand.

For the examination of the fabric of an envelope inflated with hydrogen Shakespear has modified the seam explorer above mentioned by providing it with a series of four or five guard rings at intervals of about 1 cm. so as to reduce the error due to leakage at the junction between the metal and the fabric. By this means the variation in permeability over the surface of an envelope may be observed with an accuracy of a few per cent if the instrument is calibrated against a similar piece of material of which the permeability has been measured in any of the usual ways. The necessity for the use of a sensitive mirror galvanometer limits, however, the number of observers who could be entrusted with the instrument in an airship shed.

A less accurate but more robust and portable apparatus is that known as Short's detector, which depends on the difference between the rates of diffusion of air and of hydrogen through very fine pores. A shallow cylindrical chamber is bounded on one face by a plate of porous clay, the other face being formed by a wire gauze, whose purpose is chiefly to protect the clay plate: the gauze is applied to the fabric to be examined, and hydrogen leaking through the latter diffuses through the clay. On the other side of the plate is a second small air chamber, the pressure in which is indicated by a sensitive aneroid barometer. The porous plate is selected to have a porosity forming a compromise between the requirements of maximum gas-tightness to hydraulic flow of gas and minimum resistance to molecular flow. Rates of leakage over the area of fabric tested corresponding with permeabilities of 25 lits. per sq. m. per day can be detected with some of these instruments, and they can, of course, be roughly calibrated by means of samples of fabric of known permeability. After each test it is necessary to flush the aneroid

[1] *A.C.A. Rep. and Mem.*, 1919, No. 614.

chamber with pure air. The comparatively low sensitivity makes the apparatus suitable only for locating areas of excessive permeability: the variability of the porous plates also makes the sensitivity somewhat inconstant. But the instrument has been of considerable service in detecting points where mechanical damage has occurred or where seams have become poorly adherent.

§ (10) Permeability of Balloon Fabrics by Air and by other Gases: Behaviour of Hydrogen in a Balloon.—As may be expected from the classical experiments on the permeability of stretched rubber films, rubber-proofed balloon fabrics which are permeable by hydrogen are also permeable, but in a smaller degree, by air. After a balloon or airship has been inflated, losses of hydrogen occur by permeation through the envelope and by effusion through defective seams, etc., even while it is at rest in its shed. If the envelope is in good condition the daily loss from such causes is less than that occurring during one flight when gas is allowed to escape through the valves in the course of various manœuvres, especially when landing. The quantity of gas has to be replenished before the next excursion, in order to regain the original lifting capacity. In order to prevent inflow of air through actual pores the internal pressure of the balloon is always maintained in excess of atmospheric, either by the use of the ballonet, or by the introduction of fresh hydrogen; consequently leakage of gas through any such pores will be constantly occurring. In itself, therefore, a high permeability by hydrogen merely results in some additional expense for refilling, which is only a fraction of that necessarily incurred in normal flights. But high permeability by hydrogen may be expected to be accompanied by high permeability by air. The hydrogen lost can be replenished: the air which enters will accumulate until eventually the whole contents of the gas-bag have to be discharged owing to it having become impossible to obtain sufficient lift. Balloons are usually so designed that this must occur before the purity of the gas has been reduced to 80 per cent: the figure was presumably originally selected as being somewhat above that at which a mixture of hydrogen and air becomes explosive. More recent experiments have shown that mixtures somewhat richer than this are capable of exploding, and the working limit should be made still higher owing to the fact that the air which enters is richer in oxygen than ordinary air. If the whole quantity has entered by true "permeation" the gas will become explosive when its purity has fallen to 88 per cent or thereabouts.

Austerweil[1] made a number of analyses of gas from airships to show the increase in relative proportion of oxygen in the air which entered through the rubber: in one case, where the purity had fallen to 78·3 per cent, the ratio of oxygen to nitrogen was 36·4 to 63·6. By analysing the residue of gas in a Renard-Surcouf balance after a permeability test on a cold vulcanised fabric he found (1) that the oxygen averaged 45·7 per cent of the air which had entered, and (2) that the volume of hydrogen which escaped was 5·9 times that of the "air" which entered. From records of the gas consumption and rate of loss of purity in two airships over the same period he deduced the following permeabilities for the envelopes at an average temperature of 18° C.:

Steam-vulcanised fabric 77 lits./m.²/day hydrogen, 14 lits./m.²/day "air."

Cold-vulcanised fabric 60·7 lits./m.²/day hydrogen, 5 lits./m.²/day "air."

Over a period when the average temperature was 4° C. he found the rate of loss of lift less by 8 per cent for the former and by 68 per cent for the latter, indicating a larger temperature coefficient though smaller absolute value of air permeability for the cold-cured fabric. These results are mentioned here, although several more accurate determinations of air permeability have since been made, because later workers do not appear to have used cold-cured fabrics, and the difference, if it can be confirmed, would point to a useful superiority of such fabrics in this connection.

Austerweil also measured the permeability of balloon fabric by arseniuretted hydrogen: calculation from his figures indicates that this is about nineteen times the permeability by hydrogen. He points out that other impurities which may occur in hydrogen, such as phosphoretted and sulphuretted hydrogen, also have very high permeabilities, so that it is improbable that they have any effect in the deterioration of the fabric as was at one time supposed.

In tests by a similar method made by Ritchie (*loc. cit.*) on a 200-litre balloon, permeabilities were found for hydrogen, oxygen, and nitrogen of 20 lits., 1·9 lits., and 1·4 lits. per sq. m. per day respectively, the oxygen and nitrogen results having been corrected to a partial pressure of 100 per cent. The low value of the air : hydrogen ratio is attributed to leakage through seams. The combustion method used for permeability determinations in his laboratory does not lend itself very well to measurement of the permeability by air, but he quotes results obtained for seven different fabrics which indicate that the permeabilities by oxygen were 0·25 to 0·32 of that by hydrogen: one observation

[1] *Loc. cit.* p. 57 *et seq.*

of permeability by nitrogen gave for this 0·14 of that by hydrogen.

More extensive results were obtained by Shakespear, Daynes, and Lambourn[1] using a suitable modification of the apparatus described in § (8). They measured not only the permeabilities to oxygen, nitrogen, and air, but also the temperature coefficients over the range 12° C. to 20° C. of some kite balloon fabrics having a hydrogen permeability about 9 lits./m^2/day at 15°·5 C. A number of experiments were also made with carbon dioxide. They found that—

(i.) The permeability by "air" is, within the limits of error (±1 per cent) of the experiments, the same as that calculated from the separate permeabilities by nitrogen and oxygen, assuming that the rates of permeation are proportional to the partial pressures of those gases in the air.

(ii.) The permeability by carbon dioxide is the same within 2 per cent whether air or hydrogen be on the "receiving" side of the fabric.

(iii.) The mean values of the permeabilities at 15°·5 C. of the following gases into hydrogen through the fabrics examined, that of hydrogen into air being taken as unity, and the mean temperature coefficients at 15°·5 C., that for hydrogen into air being 3·9 per cent, were:

	Relative Permeability.	Coefficient per cent.
Air	0·207 (·202 to ·216)	7·2
Nitrogen . .	0·143 (·137 to ·148)	7·7
Oxygen . . .	0·419	6·3
Carbon dioxide	2·73 (2·70 to 2·76)	4·7

The much higher temperature coefficient for air than for hydrogen permeability may be noted—if the logarithmic relation suggested in § (9) (iv.) held for the former also, air would enter at about 66° C. as fast as hydrogen escaped through rubber. Dewar found a higher coefficient for air than for hydrogen in his work with rubber films (§ (3)). The lower temperature coefficient observed for oxygen than for nitrogen is in accordance with Graham's result in § (2) that "dialysed" air is richer in oxygen at 4° C. than at 20° C.: for "air" he found a coefficient of 5·6 per cent at 15°·5 C.

Another series of experiments on the permeability of rubbered balloon fabrics by gases other than hydrogen is reported by Edwards and Pickering.[2] Their measurements were made with fabrics showing permeabilities by hydrogen of the order of 10 lits. per sq. m. per day, presumably at 25° C., this being the standard temperature adopted by the Bureau of Standards for such work. The gas interferometer was employed in all the estimations, except for that of ammonia, for which a chemical method was used. The permeabilities observed, relative to that of hydrogen as unity, were:

Oxygen	0·445 (·430 to ·461)
Nitrogen	0·160 (·140 to ·172)
Carbon dioxide . .	2·88 (2·80 to 2·95)
Helium	0·65 (0·57 to 0·73)
Ammonia	8·02 (7·99 to 8·04)
Ethyl chloride . . .	198 (190 to 218)
Methyl chloride . .	18·5 (18·1 to 19·4)

The helium permeability agrees well with a determination made by the writer[3] using limited quantities of the gas. The oxygen, nitrogen, and carbon dioxide figures are lower than Shakespear's, as was to be expected from the higher temperature coefficients compared with hydrogen, since the present tests refer to 25° C. instead of to 15°·5 C. From their values for oxygen and nitrogen, and Rayleigh's value for argon, Edwards and Pickering calculate that the permeability by air is 0·22 of that by hydrogen, and that the composition of the air which permeates through balloon fabric is nitrogen 56·8 per cent, oxygen 42·8 per cent, argon 0·9 per cent. As regards the effect of temperature, they give curves for hydrogen, helium, and carbon dioxide which show that the temperature coefficients of permeability at 15° C. are 3·9 per cent, 4·4 per cent, and 4·6 per cent respectively, and that their permeabilities at 100° C. are respectively 22, 17, and 17 times those at 0° C.

§ (11) Permeability by Water Vapour.—In addition to the gases and vapours mentioned above, water vapour has also been examined in respect of its permeation through balloon fabric. Rubber is commonly regarded as a waterproof material, but from the generalisation mentioned in § (3) it would appear reasonable, since water has a high critical point, to expect a considerable solubility of water vapour, and hence a high permeability. That this was not early observed may be attributed to the fact that at ordinary temperatures the possible partial pressure of water vapour in any space is small, being 1·6 per cent in air saturated at 15° C. In the above-cited paper of Edwards and Pickering the results of a few experiments are given, in which a sheet of rubber was cemented over the top of a shallow dish of 8 cm. diameter containing phosphorus pentoxide: the closed dish was placed in an atmosphere saturated with water vapour at 25° C., and the rate of increase in weight determined. Using sheets of "dental dam"

[1] *A.C.A. Rep. and Mem.*, 1918, No. 622.
[2] *Bureau of Standards Sci. Paper*, 1920, No. 387.
[3] *A.C.A. Techn. Rep.*, 1915.

of 0·18 and 0·25 mm. thickness, the permeabilities observed (calculated for a difference in partial pressure of water vapour at 0° C. of 760 mm. of mercury, from the figure actually obtained for about 20 mm. partial pressure) were 47 times and 62 times the permeabilities by hydrogen. In other experiments the upper surface of the rubber was in contact with liquid water, and the calculated permeabilities were 95 times and 115 times that by hydrogen for sheets 0·21 mm. and 0·25 mm. thick. It may be noted that in both series the thicker and less permeable material gave the higher ratio, but the authors do not claim much accuracy for the results, since successive tests differed in some cases by as much as 20 per cent from the means.

Measurements of the permeability by water vapour were also made (1919) by the Air Ministry. These were made on proofed fabric, and included tests at several different temperatures. In addition to a static method similar to that used by Edwards and Pickering, a modification of the usual "constant flow" method was also employed in which air saturated with water vapour, or, at 100° C., steam itself, passed over one surface of the fabric and dry air over the other. Both methods indicated that the permeability calculated as above was of the order of 200 times that by hydrogen, and that the temperature coefficient was small and probably negative. Actually, of course, the weight of water collected per hour was greater at the higher temperatures, but the factor by which it was multiplied to correct to a partial pressure of 760 mm. of mercury became smaller. The results are about four times as high as those of Edwards and Pickering above-mentioned. If the difference is due to the difficulty, on which both articles comment, of ensuring instantaneous removal of the permeating vapour from the "dry" side of the rubber, which tends to give low results, it may possibly be ascribed to the presence of the hygroscopic textile in the tests last described, which would probably assist in this removal. But a qualitative observation by Dewar [1] on a rubber film gives a permeability only about 25 times that by hydrogen for permeation into a vacuum. Hence the differences are probably in the films used. Reference may be made in this connection to a determination made by Tangl [2] of the diffusion constant of water in rubber, which is given as 98×10^{-6} cm.²/day: on the usual theory of permeability this would require a very much greater solubility of water in rubber than actually occurs, but Tangl's method was not capable of much accuracy, nor were the assumptions on which his constant was calculated free from objection.

It may be of interest to illustrate the approximate error due to water vapour which the use of rubber tubing is likely to cause in chemical and physical experiments. We shall assume the specific permeability by hydrogen to be 4×10^{-7} cm.-sec. units (see § (3)) and take the higher of the above water vapour-hydrogen ratios as more probable. If the thickness of the wall of the rubber tubing is 1 mm. and it is in contact with substantially dry air on one side and on the other with air 75 per cent saturated at 25° C., there will pass through every sq. cm. of the rubber area 0·06 c.c. of water vapour (measured at N.T.P.) per hour: this weighs 0·05 mgm. and is sufficient to raise to the above degree of saturation about 3 c.c. of air per hour. In vacuum work this leakage of water vapour would correspond with an influx of 45 c.c. per hour, measured at a pressure even so high as 1 mm. of mercury: the air leakage through the same rubber would account for only some 2 c.c. per hour under these conditions.

§ (12) Permeability by Various Gases.—The table on the following page summarises the results obtained by various workers for the permeability of rubber films and of rubbered balloon fabric by different gases. The early results other than those of Graham have not been included, except such as relate to gases not since studied more accurately. The figures are all relative to the permeability by hydrogen. For approximate computations a specific permeability by hydrogen may be assumed equal to about 4×10^{-7} c.c. per sq. cm. per sec. per cm. thickness at 25° C., but it must be remembered that different samples of rubber may show very different apparent specific permeabilities, especially if in very thin sheets.

§ (13) Theory of Permeability of Proofed Fabrics.—The phenomena exhibited by rubber films and by rubber-proofed fabric have been separately treated, partly because this was convenient in view of the different methods used for the measurements, and partly because there appear to be certain differences between the properties of the rubber in the two conditions. Thus:

(i.) Although the experiments of Daynes and of Edwards and Pickering appear to show fairly definitely that the permeability of a sheet of rubber is inversely proportional to its thickness, in accordance with Wroblewski's theory of the process involved, there are several observations which point to this generalisation being inapplicable to rubbered fabrics. If several pieces of balloon fabric are superposed, the resulting permeability P is found to be given by $1/P = 1/p_1 + 1/p_2 + \ldots$, where p_1, p_2, etc., are the permeabilities of

[1] *Roy. Inst. Proc.*, 1915, xxi. 559.
[2] *Ann. d. Physik*, 1911, xxxiv. 311.

Gas.	Relative Permeability of Rubber Film.	Relative Permeability of Balloon Fabric.
Air	0·21 G, 0·18 D, 0·19 Da	0·21 S, 0·22 E
Ammonia	11·3 Da	8·0 E
Argon	0·20 R, 0·23 D	..
Arseniuretted hydrogen	1·3 M	19 A
Carbon dioxide	2·46 G, 2·50 D, 2·75 Da	2·73 S, 2·88 E
Carbon monoxide	0·20 G, 0·17 D	..
Cyanogen	10 M	..
Ethyl chloride	..	198 E
Ethylene	1·3 M	..
Helium	0·31 D	0·66 B, 0·65 E
Hydrogen	1·00	1·00
Methane	0·39 G	..
Methyl chloride	..	18·5 E
Nitrogen	0·18 G, 0·125 D	0·14 Ri, 0·14 S, 0·16 E
Nitrous oxide	4·53 Da	..
Oxygen	0·46 G, 0·36 D, 0·34 Da	0·28 Ri, 0·42 S, 0·45 E
Sulphuretted hydrogen	13 M	..
Water vapour	..	50 E, 200 EB

D = Dewar at 15° C.
Da = Daynes 17° C.
G = Graham.
M = Mitchell.
R = Rayleigh.
A = Austerweil.

B = Barr at 20° C.
E = Edwards and Pickering at 25° C.
EB = Report to Committee on Electrification of Balloons.
Ri = Ritchie (at 15·5° C. ?).
S = Shakespear, Daynes and Lambourn at 15·5° C.

the separate layers.[1] If, however, balloon fabrics have two or more layers of rubber in their construction, as has been usual in two-ply and three-ply airship fabrics, the permeability of the product is not much lower than that of a fabric having only one layer, even though the layers are of the same weight in the two cases: thus Ritchie cites statistics of tests on two-ply and three-ply fabrics made by one firm at one period showing that the average permeability of the two-ply material having one main layer of rubber of 75 gm. per sq. m. was 8·0 lits. per sq. m. per day, while that of a three-ply fabric having two layers of 85 gm. each per sq. m. was 7·65 lits. The facings of 20 gm. per sq. m. on the two-ply and of 15 gm. and 40 gm., the latter including pigments, on the three-ply fabric may be neglected in the comparison as they contribute very little to the gas-tightness. Ritchie attempts to explain this by the observation that the two layers of rubber in the three-ply fabric are not quite separate, but are connected by filaments of the same material which bridge over the interstices between the yarns. The action of the textile obstacle is presumably considered as analogous to that of the perforated film of celluloid in the experiments on gaseous and liquid diffusion mentioned by Brown,[2] who showed that owing to the increase in concentration gradient in the neighbourhood of the apertures no sensible decrease in total flux was produced by the interposition of the septum into a column of air or jelly. But this would not explain the present difficulty, for the concentration gradient of gas in rubber must be halved if the rubber layer is twice as thick: it would only account for the flow through a sheet of given thickness being independent of the blocking of part of its area by an impervious screen.

(ii.) The average permeability by hydrogen of modern airship fabrics is rather less than 10 lits. per sq. m. per day. This degree of gas-tightness can sometimes be obtained with proofings of rubber weighing 80 gm. per sq. m., but if the weight allowed reaches 200 gm. per sq. m. no particular improvement is obtained above that resulting from the more usual 100-110 gm. per sq. m. except that very poor samples are of less frequent occurrence. Permeabilities lower than about 4 lits. per sq. m. per day have scarcely ever been observed unless the rubber has begun to oxidise, when the resinous product may reduce the leakage to an inappreciable quantity. Consequently it has been stated that the permeability is not inversely proportional to the thickness and Fick's law of diffusion cannot therefore apply.

(iii.) The "specific permeability" of rubber in the form of an unsupported film is considerably higher than that of rubber spread on a fabric. Shakespear[3] found from measurements on films and on proofings made by the

[1] Shakespear, *A.C.A. Rep. and Mem.*, 1918, No. 447, and Ritchie, *ib.*, 1919, No. 584.
[2] *Chem. Soc. Trans.*, 1918, cxiii. 583.
[3] *A.C.A. Rep. and Mem.*, 1918, No. 447.

evaporation of a rubber solution on a textile, that the rubber was twice as efficient in the latter condition, and concluded that the textile itself was the most important factor in obstructing leakage in a balloon fabric, the rubber serving merely to caulk the interstices between the threads. Ritchie (*loc. cit.*) mentions that the best film he was able to make of weight 100 gm. per sq. m. had a permeability of 15 lits. per sq. m. per day, and suggests that the rubber deposited from solutions tends to agglomerate into drops leaving capillary apertures between them. Edwards and Pickering [1] also point out that the permeability calculated for a weight of 120 gm. per sq. m. from their measurements on different films from 0·2 mm. to 2 mm. thick is about twice that observed for commercial balloon fabrics having the same weight of rubber.

(iv.) Some of these differences may readily be explained without resort to any unusual hypotheses. The lack of proportionality between "obstructiveness" (Shakespear's term for the reciprocal of permeability) and thickness of proofing or number of layers of rubber is probably due in part to the natural tendency of a works to exert greater care in the preparation of a light proofing than of a heavy one. It has been found that the best results are obtained with a given weight of proofing when the application is made in a large number of coats, the fabric being reversed before each passage under the knife of the spreader. By this means the probability of uniformity in the layer is much increased, holes or thin places left at one passage being covered at the next. The number of coats applied may be twenty or more: obviously the greater the number of coats the less the production of the machine, and the greater the waste of solvent, so that if an operative can secure satisfactory gas-tightness with twenty coats, giving a total weight of 100 gm. per sq. m., he is not likely to apply forty coats for a total of 200 gm. per sq. m.

Further, the removal of solvent from a heavy proofing is more difficult than from a light one, and the evolution during vulcanisation of the traces remaining after drying would tend to give the thicker rubber a more porous structure than the thinner. These two suggestions may possibly explain, to some extent at least, the points raised under (i.) and (ii.) above.

The difference in obstructiveness between rubber in the conditions of an unsupported film and of a proofing may also be explained by the more homogeneous structure of the latter, so far as the results of Edwards and Pickering are concerned. The exact details of the methods of making the films used by Ritchie and by Shakespear are not stated, but two possibilities of difference between the films and proofings may be noted. Ritchie compares his best film with commercial proofings, though it is stated that the method of production of the film was different from that used in manufacture, *e.g.* the films were built up on a rigid impermeable support. Presumably the consistency of the solution was not similar to that of the "dough" used in spreading, and the degree of breaking-down of the rubber complex would be different. To the influence of "depolymerisation" we shall refer later. Shakespear cites in support of his contention that the textile is of more importance than the rubber the fact that he was able to produce a proofed fabric nearly four times as efficient as the best manufactured balloon fabric by acting on this hypothesis: by this may be inferred that he used thin solutions of rubber so as to obtain better penetration. Since Ritchie states that examination of textile which has been soaked in solution shows that the solution does not penetrate the yarns, it may be concluded that the improvement obtained by Shakespear was largely the result of the use of thin solutions and greater uniformity in the structure of the rubber layer.

These remarks are not intended to negative the possibility of the textile contributing towards the impermeability of a proofed fabric. The diffusion of hydrogen *along* the yarns is not extremely rapid (§ (9) (i.)), and that *across* the yarns may be considerably slower, since many fibres are twisted closely together in the yarn. Shakespear's theory requires that it should be negligibly slow in comparison with the rate of permeation through rubber, unless the improvement in obstructiveness which he obtains is accompanied by an alteration in the ratio of permeabilities by different gases in the direction required by Graham's law. It is desirable that comparisons be made between films and proofings produced from the same rubber "solution" under precisely similar conditions.

§ (14) Composition of the Rubber. — The effect of variations in the composition and treatment of the rubber mixture upon the permeability has not received adequate attention. The extent of the working to which the rubber has been subjected in the processes of washing, mixing with sulphur, and kneading with solvent affects the "nerve" of the rubber, and for most purposes is reduced to a minimum in order to obtain maximum strength and elongation in the product: it has been found that for obtaining impermeability the more the rubber is worked the better the result, though other considera-

[1] *Bureau of Standards Sci. Paper*, 1920, No. 387.

tions such as that of permanence set limits to the amount permissible. The term "depolymerisation" has been applied to the process involved, though the evidence is not sufficient to decide whether the effect is physical or chemical: at any rate a finer structure may be assumed to be the result. If the rubber be considered as a gel there will be less continuity in the less rigid phase, and consequently lower rate of diffusion of dissolved gas.

Closely connected with the question of the extent of working to which the rubber has been subjected on the mixing rollers is that of vulcanisation. This is not the place for a discussion of the difficult problems arising from the attempt to obtain a clear and full understanding of the process, but briefly it may be stated that the usual view of hot vulcanisation is that when the mixture of rubber and sulphur is heated, part of the sulphur combines with the rubber, forming a more or less definite chemical compound which is, in soft rubbers, adsorbed by the unchanged material. The physical characteristics of the product are determined not only by the extent of combination, which depends *inter alia* on the time and temperature of vulcanisation, but also by the physical condition or structure of the original mixture, *i.e.* by the nature and extent of the surfaces at which adsorption occurs. The criteria of good vulcanisation are, for most rubber goods, the tensile strength and extensibility and the permanence of the product: roughly, under-vulcanisation results in low tensile strength, over-vulcanisation in small extensibility, and under-vulcanised products are more prone to oxidation and are more sensitive to heat and cold, while over-vulcanisation tends towards eventual brittleness. To a small extent, vulcanisation may continue after the article has cooled to room temperatures, since there remains an excess of sulphur, dissolved or otherwise distributed throughout the mass, capable of combining with more rubber. This "free" sulphur is distinguished from the "combined" sulphur by the fact that it may be extracted by many solvents: for a given mixture the extent of vulcanisation is measured by the quantity of "combined" sulphur. The estimation of this constituent is, however, no accurate index of the vulcanisation, for rubber which has been "killed" by long working on the rollers requires much more sulphur to be combined with it to produce optimum vulcanisation than does less worked rubber. From the colloidal point of view, this is because the former has more surface for adsorption. The degree of vulcanisation of proofings such as are used in balloon fabrics can only be judged by such qualitative tests as the behaviour with benzene and by the permanence of the product, since the elastic properties are very poor and the preparation of a test piece would in any case be extremely difficult.

The immediate effect of vulcanisation on the permeability is not great, though in such cases as have been examined there has usually been a small decrease. Edwards and Pickering (*loc. cit.*) mention two series of tests in which the time of vulcanisation varied from nil to 1·5 hours at 140° C., causing the quantity of combined sulphur to increase from 0·3 to 2·5 per cent, without any appreciable variation in permeability. In a series in which all the samples were over-cured, increase in the combined sulphur from 1·6 to some 5·0 per cent reduced the permeability from 20 lits. or more to 11 or 15 lits. per sq. m. per day. In the latter series the most highly over-cured pieces became brittle on storage for a year, and in this condition gave leakages of only 1·5 to 4·0 lits. when re-tested without crumpling. It is indeed in connection with the ageing of balloon fabrics that the influences of vulcanisation and of the treatment prior to vulcanisation are of most serious importance. The "depolymerisation" of the rubber, which is desirable for the attainment of initial impermeability, leads not only to a greater requirement of sulphur for vulcanisation but also to greater general reactivity. With the increase in sensitiveness towards oxidation, we are not here concerned: the singular variations in permeability which occur on exposure of balloon fabrics to light are dealt with in the article on "Airship Fabrics" (*q.v.*). The "depolymerised" rubber seems to be capable also of partial repolymerisation on storage, with the result that certain samples have been found to show inconstant permeability even when stored under ideal conditions. In addition to the cases of rapid variation mentioned in the section "duration of test," there may be cited three balloon fabrics studied by Edwards and Moore,[1] of which one gave a permeability of 15·4 lits. during the first few months after manufacture, and of 19·2 lits. after twelve months' storage, while two others increased from 18 to 24 lits. and from 17 to 19 lits. in eleven months.

The free sulphur in hot-cured rubber exists at first in an unstable form (colloidal sulphur, sulphur μ), which has a higher vapour pressure than crystalline sulphur and diffuses towards any small crystal which may be formed, giving rise in certain cases to the phenomenon of "bloom" or "sulphuring up," *i.e.* of the formation of numerous crystals at the surface. Edwards and Pickering (*loc. cit.*) give a microphotograph of a section through a piece of

[1] National Advisory Committee for Aeronautics, Washington, *Report* No. 39, 1919.

balloon fabric which showed crystals in the rubber, but state that tests made on a portion of the same fabric where crystallisation was extensive showed no significant increase of permeability above portions where crystallisation had not occurred. Austerweil mentions, however (*loc. cit.* p. 74), that samples of fabric taken from a dirigible which had been constructed a year previously showed permeabilities of 8, 13, 24, and 67 lits., the percentages of combined sulphur being 0·93, 0·89, 0·77, and 0·58 in the respective test pieces. He ascribes the higher permeabilities to the evaporation of some of the free sulphur (the total sulphur was 4 per cent) from the less vulcanised pieces. The slow increases in permeability on storage mentioned in the last paragraph may actually be due to this cause rather than to "repolymerisation" of the rubber.

The above discussion of the effects of vulcanisation on permeability has been concerned solely with balloon fabrics vulcanised by the "hot cure" (steam or air heating). Another method has been used to some extent, but has not found favour in this country, though it was used with some success in France as early as 1909. In this method no sulphur is included in the rubber mixture, vulcanisation being effected by means of the vapour or of a solution of sulphur chloride; since little heating is required, this is known as the "cold cure." Rubber cured by these processes is usually less permanent than the best hot-cured rubber, and there is always a possibility, as far as proofed cotton is concerned, that traces of sulphur chloride may be left in the rubber unless the utmost care is exercised. In the presence of moisture this gives rise to acidity, with disastrous effects on the textile. The danger of acidity can be and has been obviated: as regards permanence, exposures to the weather have not always indicated superiority of the hot-cure, and it is possible that the alleged difference may apply only to rubber which has not been subjected to the prolonged "working" necessary for obtaining low permeability. It appears to be easier to secure good gas-tightness with the cold cure: leakages as low as 5 lits. per sq. metre per day were found for some French samples examined by the writer in 1911. In this connection reference may be made to the figures cited above from Austerweil's book which indicate a lower rate of air permeation through cold-cured fabric, though this result has not been tested by any later experiments.

The fact that the rate of interdiffusion of hydrogen and air when not separated by any membrane is not too rapid to prevent the recognition of local variations in the proportion of air in the hydrogen of a balloon, has been known for some time from the behaviour of spherical balloons. Caro and Schuck [1] determined the percentage of air in the gas of a 650 cubic metre spherical balloon at various levels after it had rested for twenty-four days in its shed and showed that the percentage of nitrogen gradually decreased from 18·6 at 2 metres from the bottom to 11·4 at the top, 10 metres above; during this time 185 cubic metres of hydrogen had been lost and 74 cubic metres of air had entered, and according to their analyses this air did not differ much in composition from ordinary air. But Ritchie [2] notes that air, which from its amount and composition must have entered by permeation through the whole envelope of an airship, tends to accumulate at the bottom of the envelope. Thus samples taken from the bottom of a certain ship six days after inflation showed on analysis 96·52 per cent hydrogen, 0·91 per cent oxygen, 2·27 per cent nitrogen, while samples taken from the side at 12 feet above the bottom gave 98·83 per cent hydrogen, 0·21 per cent oxygen, 0·65 per cent nitrogen. Ritchie deduces from these and other similar observations that the entering air tends to diffuse along the surface of the rubber facing of the proofed fabric more rapidly than at right angles thereto, *i.e.* than into the body of the gas. It is perhaps more probable that the reason may be found in a higher rate of diffusion along the textile between the facing and the main rubber layer than through the facing: in the shell of cotton the gases from the air would tend to accumulate at the bottom in virtue of their greater density.

§ (15) Membranes other than Rubber.—In the preceding pages no mention has been made, except incidentally, of the passage of gases through membranes other than rubber. The extensive use of the latter substance in the manufacture of balloons and airships and the volume of work which has been done on the phenomena attending its use are sufficient justification for the devotion of so large a proportion of this article thereto. A few observations on other membranes have been made at various times and these may be here summarised.

(i.) *Soap Films.*—These are of theoretical interest. Exner [3] used films made in a glass tube of 7 mm. bore from a 1·5 per cent solution of Marseilles soap in water, through which air passed at a rate of 0·64 c.c. per sq. cm. per minute. He found that the rates of permeation by twelve different gases and vapours agreed within some 3 per cent with those required by the law, that the perme-

[1] *Chemiker Zeitung*, 1911, xlv. 406.
[2] *A.C.A. Rep. and Mem.*, 1919, No. 584.
[3] *Pogg. Ann.*, 1875, (6), clv. (v.), 321, and *Beiblätter*, 1878, ii. 199.

ability varied as $A/\sqrt{\rho}$, where A is absorption coefficient and ρ the density of the gas; but oxygen passed through the film 20 per cent too fast and ether vapour much too slowly. These results were confirmed by Pranghe,[1] for air, coal-gas, hydrogen, and oxygen. McLennan and Shaver have recently [2] examined soap films prepared according to Boys' formula: the rates of escape of hydrogen and helium at 20° C. through films at the red-green stage were respectively 4·0 and 28 c.c. per cm.^{2} per hour.

(ii.) *Linseed Oil.* — Lamellae of unboiled oil were examined by Pranghe (*loc. cit.*) to see if Exner's law applied to these. The permeability relative to air was found to be coal-gas (density 0·48) 2·8, carbon dioxide 16·8, hydrogen 2·8, nitrous oxide 16·8. The last-mentioned gas diverged considerably from the law. Varnishes made from boiled linseed oil with various additions have frequently been used in proofing balloon fabrics. The permeability obtained may be as low as 0·5 lit. per sq. metre per day. According to Austerweil (*loc. cit.* p. 111) such proofing has the great advantage over rubber and other substances, that the permeability by air is negligibly small, even when the hydrogen figure is 2·5 lits. The causes which have led oil proofings to be now little used are (i.) liability to destruction of cotton in contact with them owing to acidity of the oil; (ii.) liability to spontaneous heating and possible inflammation, when packed; (iii.) inconvenience of the tacky nature of the surface; (iv.) difficulty of seaming and repairing. Varnishes with a linseed or tung oil base are still used, however, for protecting goldbeaters' skin.

(iii.) *Gelatine* has been proposed as a proofing for balloon fabrics, either alone or in contact with rubber, but though very good gas-tightness can be obtained by its means, the necessity for the addition of hygroscopic substances in order to maintain pliability, together with the liability to decomposition by fungi and bacteria, has prevented any extensive use. The permeabilities of gelatine jellies by various gases were measured by Hagenbach,[3] and carbon dioxide, nitrous oxide, hydrogen, sulphuretted hydrogen and ammonia gave very rough approximation to Exner's law when the absorption coefficients of these gases in water were used in the formula: oxygen appeared to be lost some 7·5 times as fast as theory required. The concentration of the jelly influences the absolute rate considerably: for concentrations 0, 10, 15, and 20 per cent the relative permeabilities were respectively 1, 0·71, 0·67, and 0·59.

[1] *Beiblätter*, 1878, ii. 202.
[2] *Phil. Mag.*, 1920, xl. 272.
[3] *Wied. Ann.*, 1898, lxv. 673.

(iv.) *Nitrocellulose and acetylcellulose* have been used with some success as "dopes" to reduce the permeability of rubbered fabrics, though no fabrics have come into practice in which these substances form the sole proofing. Both classes of dope contain oils or other softeners: the reduction of permeability is very marked until the film begins to become brittle. The use of unsuitable nitrocellulose may cause rapid destruction of the textile of a balloon fabric. Austerweil reports (*loc. cit.* p. 100) some experiments on the application of a commercial cellulose acetate preparation, which show that the permeability by air is negligibly small.

(v.) *Goldbeaters' skin*, obtained from the caeca of cattle, is used almost exclusively in rigid airships. The skins are soaked in glycerine solution before use, in order to prevent them from becoming dry and brittle. The English practice is to stick them with rubber solution to lightly rubbered fabric; in Germany they are applied direct to the cotton, being stuck with glue. Samples of skin-lined fabric have shown permeabilities less than 0·1 lit. per sq. metre per day: mechanical imperfections raise the average figure to 1·0 lits. when the greatest care has been exercised in making the gas-bag. In *A.C.A. Rep. and Mem.* No. 360, rough figures are given for the relative permeabilities of a skin-lined gas-bag by air and by hydrogen; the hydrogen permeability being 3·2 lits. per sq. metre per day, the air permeability was 1·7 lits. The latter figure is as high as that for the air permeability of an ordinary rubbered fabric. The writer determined by a volume-loss method the permeability of a skin-lined fabric by helium and found it to be a little higher than that by hydrogen.[4] Elworthy and Murray, using a Shakespear permeameter and more ample supplies of helium, found the ratio of helium to hydrogen permeability to be unity for a fabric with a single skin and 1·3 for a sample with two skin layers.[5]

G. B.

DIHEDRAL ANGLE. See "Aeroplane, Component Parts of."

DISTORTION, MEASUREMENTS OF, in Aeroplane Wing Structures under Loads. See "Aeroplane Structures, Experiments in," § (6).

DISTURBED MOTION OF AIRCRAFT IN A NATURAL WIND: mathematical treatment. See "Aircraft, The Stability of," § (16).

DOPES: solutions used for tightening fabric on aeroplane wings. See "Aeroplane Wings, The Doping of."

[4] *A.C.A. Rep. and Mem.*, 1915, No. 232.
[5] *Roy. Soc. Canada Trans.*, 1919, xiii. (4), 37.

Composition and preparation of. See *ibid.* § (8).

Pigmentation of. See *ibid.* § (6).

DRAG: the component of the force acting on an aircraft arising from the resistance of the air, which acts in a direction opposite to that of the relative motion.

Determination of, on full-scale aeroplanes. See "Aerodynamic Research, Full Scale," §§ (10) and (12).

Measurement of, in a Wind Channel. See "Model Experiments in Aeronautics," § (7) (ii.), (iii.), (iv.).

Speed, and Angle of Attack, Effect of. See "Flight, Principles of."

DYNAMIC LIFT OF AIRSHIPS due to wind forces acting when the airship axis is inclined to the vertical, and its effect on the performance of airships. See "Airships, Experiments on," § (14).

— E —

ELEVATOR. See "Aeroplane, Component Parts of."

ELEVATORS, strength tests on. See "Aeroplane Structures, Experiments," § (18).

ENGINE POWER, variation of, with height; effect on the performance of aircraft. See "Aircraft Performance," § (5) (i.); see also "Aerodynamic Research, Full Scale," § (8).

ENGINES FOR AIRCRAFT, AIR-COOLED

§ (1) INTRODUCTORY.—Air-cooled internal combustion engines have been used for the propulsion of aircraft almost from the earliest days of practical aviation. At the present date the majority of engines are water-cooled, but in the British Flying Services up to the early part of 1916, air-cooled engines were more used than water-cooled.

Air-cooled engines were first brought into prominence by the rotary type introduced by the Société Gnome. At the date of their introduction, these engines had a reliability which compared not unfavourably with that of existing stationary water- and air-cooled types, with the great advantage of a much lower weight per horse-power. In addition their installation in almost any type of aeroplane was a comparatively simple matter. Air-cooling was not, of course, confined to rotary engines. Eight- and twelve-cylinder V-type and single- and double-crank radial engines have been in common use for a number of years. The best known V-type engines have been designed by the Renault Company in France and Royal Aircraft Establishment in England, while the Anzani Company in Italy have consistently constructed the air-cooled radial engines. The radial type has also come into prominence in England during the last few years, examples of which are the A.B.C. Company's "Dragonfly," the "Jupiter" (Bristol Aeroplane Company), and the Siddeley.

It is obvious that the chief differences between water-cooled and air-cooled engines are to be found in the design of the cylinders, but the necessity for allowing room for the cooling fins and making suitable provision for the cooling air blast exercise a considerable influence on the general design of the whole engine.

Engines may be classified as rotary, stationary line or V-type, and stationary radial, with special and intermediate types, such as the differential and X-type (multiple-crank radial). It will be convenient to consider air-cooled engines in this order.

§ (2) ROTARY ENGINES.—The peculiarity of this type from the point of view of air-cooling is that a very considerable cooling draught is provided by the rotation of the engine itself. The power absorbed in doing this is, however, considerable (*Fig.* 1), and is a serious disadvantage of this type. The effectiveness of the cooling is also open to question. Where the engine is cowled, which is the case in all modern machines, it is probable that the major portion of the air is rotating with the engine and that the relative speed of the air and cylinders is not very great.

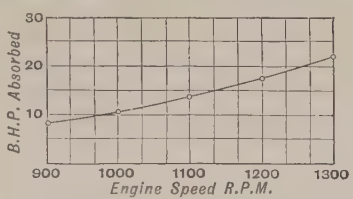

FIG. 1.—Windage Losses due to Rotation of B.R. II. Rotary Engine.

Normal b.h.p. of engine, 220 h.p. at 1300 r.p.m.

The possibilities of rotary-engine cylinder design are somewhat limited by the high centrifugal stresses imposed on any parts situated near the periphery of the engine. The centrifugal force may, in some cases, amount to as much as 1300 times gravity. This affects the design of the valves and valve gear, and incidentally the design of the cylinder head, since the valve must approximately radiate from the centre of the engine. In one respect, however, rotary engines have an advantage in that the valves and actuating mechanism may be kept in contact with the cams by the

centrifugal effect, thus eliminating the necessity of other than very light valve springs, sufficient only to close the valves when the engine is stationary.

(2) One piece all-steel—Gnome Monosoupape.

(3) Separate head, with aluminium jacket for the barrel—Bentley Rotary.

Designation	No. of Cylinders	Bore inches	Stroke inches	Speed R.P.M.	B.H.P. Complete Eng.	B.H.P. per cyl.	πP	Fuel cons. lbs. per B.H.P. per hr.	Weight of Engine (1) lbs. Complete	Weight of Engine (1) lbs. Per BHP	Weight of Engine (1) lbs. Per BHP @ 1000 R.P.M.	Weight of Cylinder (2) lbs. Complete	Weight of Cylinder (2) lbs. Per BHP	Weight of Cylinder (2) lbs. Per BHP @ 1000 R.P.M.	Compression ratio	Remarks	
130 HP Clerget	9	4·72	5·51	1200	—	13·8	94·5	·539	—	—	—	11·13	·806	·967	5	Test of Single Cylinder	Rotary air-cooled
150 HP Mono-Gnome	9	4·55	6·69	1250	152	16·9	100	·634	313	2·06	2·62	9·44	·557	·697	5·42		
B.R.2	9	5·51	7·09	1300	220	25·4	91·5	·607	496	2·16	2·81	17·0	·670	·870	5·3		Stationary air-cooled V type
R.A.E. 4A	12	3·94	5·51	1800	160	13·35	87·7	·675	637	3·98	7·16	16·38	1·225	2·20	4·2		
R.A.E. 4D	12	3·94	5·51	1800	196	16·35	107	·532	670	3·42	6·15	14·75	·903	1·62	4·7		
Dragonfly Mark II	9	5·5	6·5	1650	294	32·7	101·5	·645	670	2·27	3·75	24·25	·74	1·22	4·51	21 TD cyls. on Dragonfly crankchamber	Stationary Radial air-cooled
R.A.E. 21	9	5·5	6·5	1650	348	38·7	120	·52	695	1·99	3·29	27·0	·70	1·15	5·3		
Wasp	7	4·5	6·0	1800	153	21·9	99·1	·603	294	1·92	3·45	13·0	·594	1·07	4·0		
R.A.E. 22 TW	7	4·5	6·0	1800	187	26·8	127	·52	332	1·76	3·18	18·4	·686	1·24	5·3		
Siddeley Radial No. 2	—	5·0	5·0	1700	—	24·95	119·6	·53	—	—	—	17·3	·694	1·18	4·7	Test of Single Cylinder	
R.A.E. 19T	—	8·0	10·0	1400	—	116	130·3	·52	—	—	—	126·0	1·087	1·521	4·75	Test of Single Cylinder	
Rolls Royce Falcon III	12	4·0	5·75	2200	275	22·9	114	·53	(715) 861	3·13	6·90	(12·03) 24·2	1·056	2·33	5·4		Stationary water-cooled (3)
H/Suiza 300 HP	8	5·51	5·91	1800	300	37·5	116·8	·587	(558) 710	2·37	4·26	(22·3) 41·3	1·101	1·98	5·34		
Liberty	12	5·00	7·0	1600	394	32·8	118	·473	(825) 1049	2·66	4·26	(18·75) 39·6	1·21	1·93	5·28		

FIG. 2.—Aircraft Engines—Performance and Weights.

(1) Weight of engine includes magnetos, carburetters, induction pipes, and propeller hubs.

(2) Weight of cylinder includes valves, valve springs, valve rockers, and rocker brackets.

(3) Weights include an allowance for water and radiator of $\cdot 6 \cdot {}^{4}\sqrt{\text{bore}^2 \times \text{stroke}}$ lbs. The figures in brackets are the dry weights of engines and cylinders.

Three types of rotary-engine cylinders are in general use at the present time in Great Britain.

(1) One piece all-steel—Clerget and Le Rhone.

The results of bench tests of single cylinders and complete engines are given in *Fig.* 2.

The cooling of the cylinders on the single-cylinder test beds is probably superior to that

on the complete engines, but this advantage is to some extent nullified by the poorer cooling of the pistons. It would appear that a very large proportion of the lubricating oil in complete engines would be driven by the centrifugal effect on to the underside of the piston heads, and, once there, it could not escape since it is subject to a continuous force of several hundred times gravity. This oil must, therefore, all evaporate, and in doing so cool the piston head. This, of course, does not take place on the single-cylinder test beds.

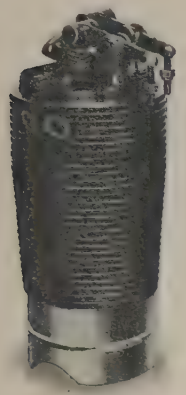

FIG. 3.—Cylinder of 130 h.p. Clerget Rotary Engine.

Type (1), which is typical of rotary-engine cylinder design, is shown in *Fig.* 3. It is machined from a single steel forging, and has integral with it the cooling fins, inlet valve port, and exhaust valve guide. At first sight the machining operations appear heroic, but special machine tools have been developed in the last few years for work of this nature, which have reduced the cost of construction in a remarkable manner. Cylinders of this type are very reliable in use, but, as would be expected, they develop rather a low mean effective pressure.

FIG. 4.—Cylinder of 150 h.p. Monosoupape Gnome Engine.

Type (2) (*Fig.* 4) has features of some interest. A single valve serves both for exhaust and the admission of the major portion of the air. This valve is closed a little before the end of the induction stroke, after which a very rich petrol air mixture is sucked through ports which the piston overruns at the end of its stroke. In order to prevent the exhaust gases from blowing back through the ports it is necessary to open the exhaust valves exceedingly early in the expansion stroke, so as to allow the exhaust pressure to fall to that of the atmosphere before the piston overruns the ports. In practice the best results are obtained by the valve opening about 95° of crank angle after the commencement of the expansion stroke.

In spite of this and the further disadvantage that the mixture in the cylinder is far from homogeneous, this engine develops a higher mean effective pressure than any other rotary engine. This is without doubt due to the single central valve and absence of induction or exhaust pipes, permitting an unusually good arrangement of cooling fins round the cylinder head, the fins being in direct contact with the surfaces requiring cooling without the necessity of employing heavy sections of metal to conduct the heat to them. The result is a very light cylinder. Such a cylinder fitted with suitable concentric valves and working on a normal cycle might give quite good results. Whether suitable valves can be evolved, however, is an open question, the difficulty of such a design being very great.

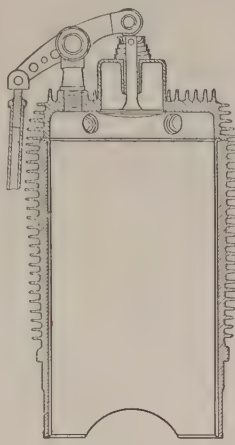

FIG. 5.—Cylinder of B.R. II. Engine.

Experiments have been carried out at the Royal Aircraft Establishment with a Monosoupape-type cylinder with direct injection, no ports, and a normal opening and closing timing for the single exhaust-inlet valve. This cylinder, 5½ in. bore by 6½ in. stroke, developed a brake mean effective pressure of 125 lbs. per sq. in. on a fuel consumption of ·5 lb. per b.h.p. hour. The compression ratio is 5·3 to 1.

FIG. 6.—Cylinder of B.R. II. Rotary Engine.

In type (3) (*Figs.* 5, 6) the barrel has a pressed-on aluminium jacket carrying the fins. It is possible that this may be more suitable for production than fins turned on the barrel, but experience with this type of

construction suggests that no improvement in cooling is obtained in this way. Owing to the thinness of the jacket it cannot be pressed on very tightly without danger of the jacket bursting either at the time of pressing on or subsequently. Even if very tight initially, it is unlikely that this fit will be maintained. Jackets removed from type (3) after a cylinder has been in service show that the contact between the aluminium and the barrel is poor. It is possible that the employment of very thick jackets might enable good contact to be maintained, but the increase in weight over that of a steel barrel with integral fins would be considerable.

§ (3) Stationary Line or "V"-type Engines.—Throughout the whole of the war V-type air-cooled stationary engines have been in continuous use in large numbers by the British Air Service. The 70 and 80 h.p. Renault engines were superseded by the 90 h.p. R.A.E. 8-cylinder, and this in its turn by the 140 h.p. R.A.E. 4A 12-cylinder. Modifications introduced from time to time after service experience have rendered this latter a very reliable engine, though the troubles experienced with it at first were very great. The 4A cylinder is made of cast iron with integral fins. The valves are in a pocket on one side, the exhaust valve being inverted over the inlet valve. The cast-iron fins are of fairly generous proportions, but there is not much finning over the flat top of the head. *Fig.* 7 shows this cylinder, and the performance obtained is given in *Fig.* 2.

Fig. 7.—R.A.E. 4A Cylinder.

In the early part of 1917 the R.A.E. 4D 12-cylinder engine was produced. It differs very little from the 4A except in its cylinders (*Figs.* 8, 9, and 10), which are of entirely different design. The head and jacket of these are cast in one piece of aluminium and an open-ended steel liner is shrunk in. The pistons are of aluminium. The valve seats are steel rings inserted in the mould before casting. The brackets for carrying the valve gear are of aluminium, integral with the cylinder. The head is spherical and of somewhat larger diameter than the barrel, and overhead valves are used. The performance, which is given in *Fig.* 2, does not compare unfavourably with the average performance of water-cooled cylinders of that date. The cylinder has, however, certain faults. Although the aluminium jacket is thicker than that of the Bentley Rotary mentioned previously, its contact with the liner is not always very good. This results in a certain amount of variation of performance between different cylinders. When this has been noticed it has nearly always been found to be due to poor contact. The 4D engine was never put into production, but a certain number are in regular use at the R.A.E. in aeroplanes used for aerodynamic experiments, and give, on the whole, no more trouble than many modern water-cooled engines. Practically no progress has been made in the last few years with the development of the V-type air-cooled engine. This is chiefly due to the greater attractions offered by the radial type of engine.

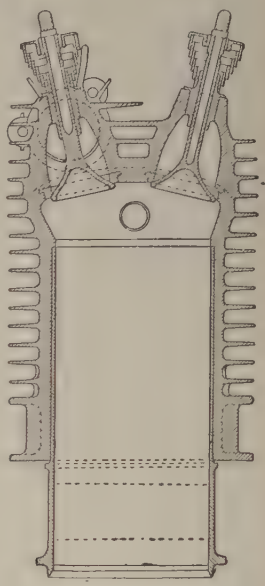

Fig. 8.—R.A.E. 4D Cylinder.

§ (4) Radial Engines. — A great deal of development work has been carried out with radial engines during the last few years. The "Dragonfly," "Wasp," "Siddeley," and "Jupiter" engines are the principal representatives of this type in England. In addition a number of cylinders suitable for the radial engines have been designed and tested at the Royal Aircraft Establishment.

Fig. 9.—R.A.E. 4D Cylinder.

FIG. 10.—Bristol Fighter Aeroplane with R.A.E. 4D Engine.

The "Dragonfly" engine (*Figs.* 11 and 12) has a one-piece solid-ended steel cylinder. There are two exhaust valves and one inlet valve, all overhead. The head is flat, of the same diameter as the barrel, and is of considerable thickness. The valves seat directly on the steel head. Separate cast-iron and aluminium castings, studded to the cylinder, form the ports for the exhaust and inlet valves and carry the valve guides. The performance obtained on test at the R.A.E. with the Mark II. engine is given in *Fig.* 2.

The "Wasp" engine cylinder is almost identical in design with the "Dragonfly" cylinder, but is of smaller size. A single cylinder has not been tested at the R.A.E., but the performance of the complete engine is given in *Fig.* 2.

FIG. 11.—Cylinder of A.B.C. "Dragonfly" Engine.

A seven- and a fourteen-cylinder engine are constructed by the Armstrong-Siddeley Company. The fourteen-cylinder engine is shown in *Fig.* 13. Performance figures for these engines are not yet available, but fairly exhaustive tests have been carried out on a single Siddeley cylinder. This cylinder has an open-ended steel barrel with integral fins, and a cast-aluminium head which is screwed on to the barrel. The valve seats in the particular cylinder tested are of steel and are placed in the mould before the head is cast. Later cylinders have bronze seats expanded in place. The cylinder head is spherical with two valves. It is very similar internally to the R.A.E. 21T cylinder described later. The valves, however, are of equal size. The finning is not quite so good as the 21T, but very excellent results have been obtained. The first cylinder failed after a short time owing to leakage past the screw thread. This was due to the growth of the aluminium which almost invariably takes place when it is subjected to heat. Previous experience has shown that the trouble due to this growth could be eliminated by annealing before final machining. The head was therefore annealed, the thread recut and screwed on hot to a new barrel with a slightly larger diameter head. The cylinder has run 100 hours with no recurrence of this trouble. This cylinder has also been run at full throttle for 15 minutes in a 30 m.p.h. cooling blast giving an ηp of 107, and for 4 minutes with no blast at all, at the end of which time the ηp was 92.

The "Jupiter" engine (*Fig.* 14) is built by the Bristol Aeroplane Company. This engine has 9 cylinders, $5\frac{3}{4}$ in. bore $\times$ $7\frac{1}{2}$ in. stroke. A small three-cylinder engine using the same cylinders is also made by this company. The cylinder of this engine consists of a solid-ended steel barrel, in the top of which are formed the seats for the four valves. Attached to the flat top of the barrel by studs is a finned aluminium casting which contains the valve ports. The top of the cylinder and this casting are carefully faced in order to obtain as

FIG. 12.—Sopwith "Snipe" Aeroplane with A.B.C. "Dragonfly" Engine.

good thermal contact as possible. The design of these cylinders, however, is undergoing

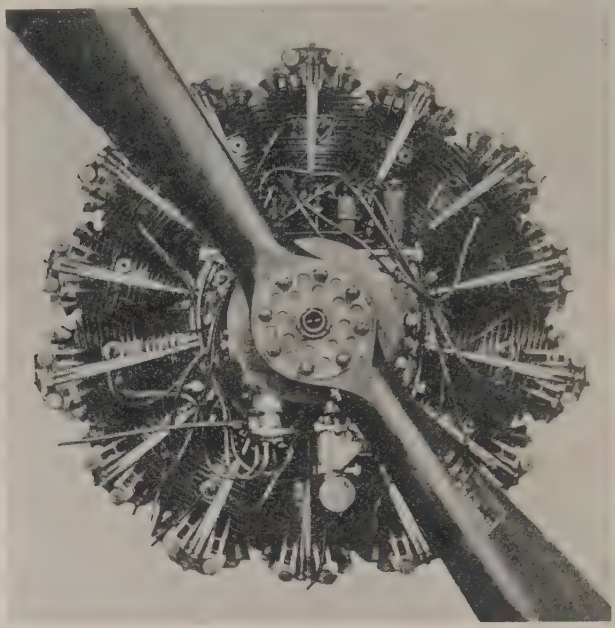

FIG. 13.—Siddeley 14-Cylinder Radial Engine.

important modifications, so that it is not possible to give useful performance figures.

Of the cylinders designed at the Royal Aircraft Establishment, the most interesting are the 21T, 22TW, and 19T. The design of the 21T will be considered in some detail, as it embodies the experience of several years of air-cooled cylinder research. The 21T cylinder (*Figs.* 15 and 16) embodies a type of construction which has already been tried successfully in smaller sizes, namely, an aluminium head cast on to an open-ended steel barrel with integral fins. This construction has been adopted for the reasons which follow: With an aluminium jacket steel barrel it is found that a considerable drop of temperature occurs across the junction of the liner and jacket, and that better results are obtained with a steel barrel having integral fins. In the case of the cylinder head, however, where an open-ended barrel is used, the superior heat conductivity of aluminium is of great advantage, especially as, owing to the presence of valves and ports, it is impossible in places to have cooling fins very close to the parts to be cooled. The ideal air-cooled cylinder, therefore, would appear to be one of composite construction, consisting of a steel open-ended barrel with integral fins and a well-finned cast-aluminium head. Various methods of construction have been used for uniting these two parts, that particularly developed at the Royal Aircraft Establishment being

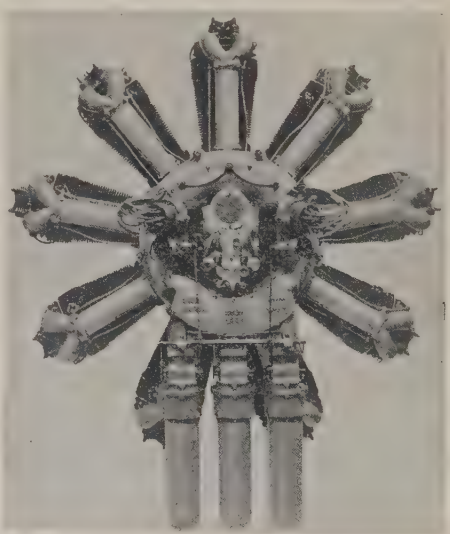

FIG. 14.—B.A.C. "Jupiter" Engine.

the casting of the aluminium head on to the steel barrel. This is the method employed in the case of the 21T cylinder.

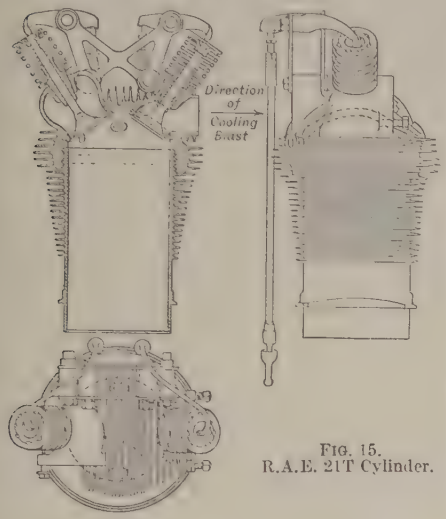

FIG. 15.
R.A.E. 21T Cylinder.

Continuing the description of this cylinder: the head is spherical, of unusually small radius. There are two valves only, the inlet being the larger. The steel brackets for the valve gear are attached by two bolts to aluminium lugs on the head casting. The radius of the spherical head is 3 in. (diameter of cylinder $5\frac{1}{2}$ in.). The object of the spherical head is not only to obtain a good shape of combustion chamber, but also to spread the upper parts of the valves well apart and allow a very good flow of cooling air across the centre of the head. It also results in keeping the general level of the outside of the inlet and exhaust passages low compared with the top of the head, so that they do not shield other parts of the head too badly from the cooling blast.

Two valves only are employed. By using only one exhaust valve the hot bridge which exists between the two valves is avoided. The valve gear, also, for a three-valve spherical head would offer a good deal of difficulty.

The method of casting the head on to the barrel is as follows: The barrel is finished machined on the outside except for squaring the holding-down flange. The bore is left with a small machining allowance. The barrel and valve seats are inserted in this mould, which is baked, and the head poured. The cylinder is then inspected and water pressure tested. If it passes, it is then machined to a finish; if not, the head is broken off and a new one cast on to the same barrel. It has occurred in one case that a fault existed which was not discovered until after the cylinder had been run. The experiment was therefore tried of casting a new head on to a completely machined barrel. This has been done in three cases, and in no case have the subsequent errors in the bore been of sufficient importance to justify scrapping the cylinder.

FIG. 16.—R.A.E. 21T Cylinder.

A set of these cylinders has been mounted on a "Dragonfly" crank chamber and the engine tested both on the bench and in flight. The bench test performance is given in *Fig.* 2. In flight the cylinders gave very good results, but the engine was unfortunately ultimately wrecked by the failure of the oil supply to the connecting-rod bearing.

R.A.E. 19T Cylinder. R.A.E. 22TW Cylinder.

FIG. 17.

The 22TW cylinder (*Fig.* 17) is merely a smaller edition of the 21T. Its performance is exceptionally good.

The 19T cylinder (*Fig.* 17) is probably far the largest air-cooled cylinder in the world at the present time. It has a bore of 8 in. and a stroke of 10 in. It was constructed in order

to determine if there were a definite limit of size for air-cooled cylinders. Like the 21T it has a cast on aluminium head, but in this case four valves are employed. The head is spherical, and particular care has been taken with finning across the centre of the head. The results obtained (*Fig.* 2) are remarkable. It should be noted that this cylinder is a good deal heavier than would be necessary on a complete engine. To suit the test-bed it had to be made about 3 in. or 4 in. longer than the stroke required, and the barrel is thicker than necessary and the fins on the barrel are too closely pitched.

Attempts have been made at the R.A.E. to attach an aluminium head to a steel barrel by means of bolts and studs. Complete success has not been obtained, but it is considered that the results are promising. *Fig.* 18 shows the method of construction employed. The conductivity of the joint is probably poor, but correct proportioning of the finning should not require good conductivity along the length of the cylinder. Thermocouple tests show that the difference of temperature between the two sides of the joints did not anywhere exceed 51° C., the aluminium side of the joint being the hotter. Except just underneath the exhaust valve the temperature difference does not exceed 20° C.

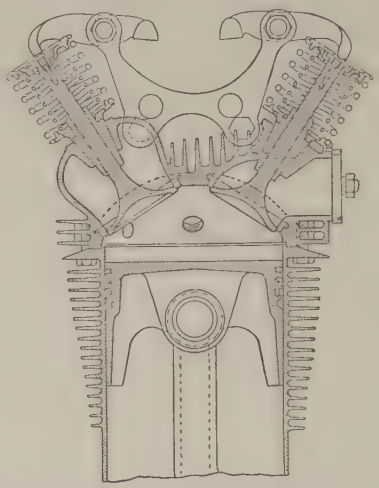

FIG. 18.—R.A.E. Cylinder, with Aluminium Head fixed with Studs and Bolts.

§ (5) COMPARISON OF ROTARY, "V"-TYPE, AND RADIAL AIR-COOLED ENGINES.—The only advantages possessed by rotary engines over the radial type are the absence of crank balance weight, the lower loading of the big end bearings, the better distribution of the mixture, and the greater experience available. These, however, all require some qualifying.

The balance weight is a pure addition to the weight of the engine and has no other disadvantage. In a radial engine having two cranks at 180° the balance weights are not very heavy. In a rotary engine the loadings on a crankpin bearing itself are, it is true, much less than in a radial engine, but in a big end bearing of the master and articulated rod type the wrist pins are much more heavily loaded in the rotary engine.

With regard to the mixture distribution this is certainly better in rotary than radial engines at the present moment, but by the insertion of a fan in the centre of a perfectly symmetrical induction system, which is possible in a radial engine, it is conceivable that the distribution might be made as good as in a rotary engine.

The greater experience available with rotary engines applies particularly to the big end bearing. The Canton Unne water-cooled radial engine, however, has been in use for a very long time. In the earlier stages of the war it was regarded as being among the most reliable engines known.

The speed of the rotary engine is limited by two factors, the high windage losses at high speed and the high centrifugal stresses. For instance, the normal speed of the "Dragonfly" radial engine is 1650 r.p.m., and that of the B.R. II., a much smaller engine, 1300 r.p.m.

The freedom of cylinder design rendered possible by the absence of centrifugal stresses allows of an ηp of 12 per cent to 20 per cent higher being obtained. The smaller gyroscopic effect in flight is of importance in high-performance machines. For instance, the Snipe with the "Dragonfly" engine is very much pleasanter to fly than the Snipe with B.R. II. or the 200 h.p. Clerget.

The oil consumption is much less on radial engines ("Dragonfly" 8 pts/hr. and B.R. II. 18 pts./hr.).

The cost of production is materially reduced owing to there being no necessity for balancing the cylinder and crank chamber. The latter can be an aluminium casting, which makes it very much cheaper than the elaborately machined steel crank chambers of rotary engines. The torque reaction is transmitted to the frame of the machine through the whole engine in the case of the radial, and through the crankshaft in the case of the rotary engine. The moment of inertia of the former about its centre line is great, while that of the latter is very small, with the result that any uneven turning moment, particularly that due to misfiring, is very much less noticeable on the aeroplane (a comparatively elastic structure) with a radial than a rotary.

Compared with the V-type engine, the radial engine has greater advantages where air-cooling is used than with water-cooling. In the case of the air-cooled V-type the cylinders have to be pitched further apart

than in a corresponding water-cooled engine, in order to allow room for adequate fins, thus making the whole engine larger and heavier, though advantage can be taken of the increased length to increase the crankshaft bearing surfaces. The water-cooled radial engine has the disadvantage of needing very complicated water connections. The result is that the water-cooled radial engine may not have very much advantage over the fixed type. The air-cooled radial engine, however, has some very marked advantages over the air-cooled V-type. It is very much lighter and there is no limit, other than considerations of weight, to the size of the cooling fins. The cylinders are all equally exposed to the propeller slipstream, whereas in the V-type special cowling arrangements are necessary and the blast velocity over the fins is generally much lower.

A modern V-type air-cooled engine might be a formidable competitor to the water-cooled engine. The point, however, is that the air-cooled radial engine has such an advantage over the V-type that it does not seem worth while at the present moment developing the latter.

The large diameter of the air-cooled radial engine is not nearly so great a disadvantage as it appears on paper. The pilot's view from most "Dragonfly" engined machines is superior to that generally obtained from aeroplanes with water-cooled engines. Moreover, it is almost certain that the cross-sectional area of aeroplane fuselages will be considerably increased in future, for other reasons than the question of engine installation.

Model experiments suggest that the head resistance of a radial engine with normal cowling is high, but the fact remains that the Snipe with a Mark I. "Dragonfly" has given a level speed (corrected) at 10,000 feet of over 140 m.p.h. From bench tests it is unlikely that this engine was giving more than 280 h.p. at 1650 r.p.m. at ground level.

§ (6) Velocity of Cooling Blast.—Assuming that an air-cooled engine will only be used for driving a tractor screw, the available cooling blast velocity at, say, two feet radius from the centre of the screw is about 20 per cent to 23 per cent greater than the aeroplane speed. For low-performance machines, therefore, the blast velocity is about 80 m.p.h., and for high-performance machines, about 95 m.p.h., at climbing speeds, and of course considerably higher when flying level. Conclusive experiments relating performance to cooling blast velocity have not been carried out, but so far, as might be expected, after a certain velocity has been reached, the increased cooling obtained with a higher blast does not appear to be very great. From the experience at present available the advantage of increased blast velocity above 100 m.p.h. would appear to be negligible. It is obvious that when the blast reaches a velocity at which the rise of blast temperature is negligible compared with the temperature difference between the cylinder and the blast, that improvement can only be looked for from increased turbulence. It must be remembered, however, that many parts of a cylinder may be subjected to a blast of quite low velocity even when the average velocity is high.

The figures given above for the available blast velocity in flight apply only to the most favourable cases, *e.g.* a radial engine with exposed cylinders. It is improbable that such a good blast can be obtained by cowling "V" or line type engines, though it may be quite sufficient for the purpose.

In connection with cooling it may be as well to point out here that power tests of air-cooled engines in which the duration of the test is only a few minutes are absolutely meaningless, and that no figures should be accepted which cannot be maintained continuously for at least fifteen minutes. It is unfortunately the case that the practice of obtaining so-called "snatch power readings" exists, with the result that extremely misleading figures are frequently quoted.

Fig. 19 shows the effect of heating up on the power developed by a "Dragonfly" engine with "Dragonfly" cylinders and with "21T"

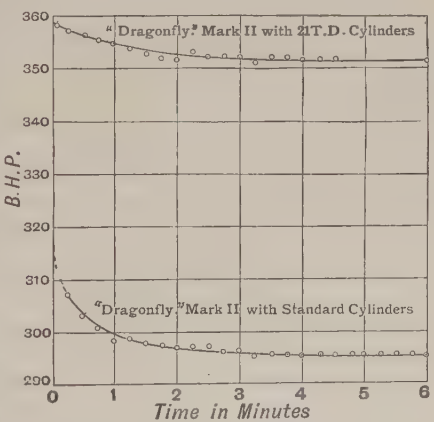

Fig. 19.—Variation of Power with Cylinder Temperature after starting up Cold.

cylinders. In each case the engine was run up to full power from cold within a few seconds of starting and brake readings taken at short intervals, while the speed was kept constant. In these two cases about 3½ minutes elapsed before the engine attained a constant temperature.

§ (7) Present-day Position of Air-cooled Engines.—Leaving out of consideration all the improvements which future experiments may render possible, it may be definitely stated that an air-cooled engine can be made:

(1) Having an ηp of 120 on the complete engine.

(2) Weight not more than 2 lbs. per b.h.p.

(3) Capable of standing full load under the same conditions as a water-cooled engine.

(4) Having a fuel consumption not exceeding 0·55 lb. b.h.p. hour.

(5) Also, though the statement cannot be made in such a definite manner, such an engine may be as reliable as any water-cooled engine. In the absence of reliable tabulated data on breakdowns in service, and the lack of service experience with the best types of air-cooled cylinders, any statement on reliability must be based on personal experience.

§ (8) The Relative Advantages of Water- and Air-cooling.—Experiments have shown that, within all practicable limits, the cooler the cylinder the higher is the thermal efficiency, in spite of the fact that the jacket losses are greater. It is possible that this is due to a partial combustion during the compression stroke, the rate of which increases with the temperature. The exhaust valve of a cylinder, however, is so much hotter than any other part of it that it is probable that nearly all this combustion takes place close to its surface, though the piston head may be partly responsible. Good cooling of a cylinder, therefore, probably only improves the thermal efficiency indirectly by lowering the exhaust valve and piston temperatures. For this reason the design of an air-cooled cylinder must be largely concerned with cooling the exhaust valve. In this respect an air-cooled cylinder must be somewhat inferior to a water-cooled cylinder, but quantitatively, as an inspection of the table in *Fig.* 2 shows, the difference is not great.

Consideration of lubrication and mechanical strength would permit water-cooled engines being run with a jacket temperature considerably exceeding 100° C., but, of course, should this happen owing to the water-cooling arrangements being inadequate or defective, the whole system fails completely. Air-cooled engines, on the other hand, are immune from any total failure of this nature, and should they run hotter than normally, owing, for instance, to unusual climatic conditions, will suffer some reduction in performance, but give no other trouble.

The saving in weight due to air-cooling may not be very great and may, in some cases, be counterbalanced by increased head resistance. Its great advantage lies in the lower capital and attendance costs, and the simplicity of the engine installation. The gain in these directions is so great that one may confidently predict a very considerable increase in the use of air-cooled engines in the future. G. H. N.

ENGINES FOR AIRCRAFT, THE EFFECT OF ALTITUDE ON THE RUNNING AND PERFORMANCE OF

§ (1) Introductory.—In the early days of aviation the maximum height reached was comparatively insignificant, and the effect on the performance of the engine negligible, but at the present day the flying range, at any rate for military purposes, may be considered to extend between sea-level and a height of 30,000 ft., and this will certainly be increased in the near future. Within these limits the variations in atmospheric pressure and temperature are very great. These variations are not constant, but a fair average for Great Britain is given in the table below. The figures are an average for the whole year. Since much more flying is carried out in summer than in winter, the average temperature for flying weather is somewhat higher. This does not, however, so much affect the figures for the higher altitudes, 15,000 ft. and over.

Variation of Atmospheric Pressure and Temperature with Altitude

Height above Sea-level. Feet.	Pressure. Lbs./Sq. In.	Temperature. ° C.
0	14·7	8·0
2,000	13·6	5·5
4,000	12·6	2·5
6,000	11·7	− 0·5
8,000	10·9	− 3·5
10,000	10·1	− 6·5
12,000	9·38	− 10
14,000	8·64	− 13·5
16,000	7·94	− 17·0
18,000	7·35	− 21·5
20,000	6·69	− 25·5
22,000	6·17	− 29·0
24,000	5·59	− 33·0
26,000	5·16	− 37·0
28,000	4·78	− 40·5
30,000	4·41	− 44·0

These variable atmospheric conditions affect aircraft engines in the following respects:

1. Power.
2. Fuel consumption.
3. Carburation.
4. Electrical ignition.
5. Cylinder cooling.

§ (2) Effect on Power.—In all ordinary internal combustion engines, including all normal aircraft engines, the cylinders are

arranged to charge themselves with air, by having their cylinders open to the atmosphere through suitable valves during the suction stroke. The result is that the cylinders are charged with air after the suction stroke at a pressure which is slightly lower than that of the atmosphere in which the engine is working.

The maximum quantity of fuel which can usefully be burned in a cylinder is obviously proportional to the quantity of air contained in the cylinder. Hence it will be seen that the quantity of fuel, and consequently the power which can be developed, is, roughly speaking, proportional to the density of the atmosphere surrounding the engine. This fact was recognised before the advent of aviation, and special arrangements have been made for stationary internal combustion engines when they have been required to work at high altitudes, such as, for instance, when supplying power to some of the mines situated in the mountainous districts of South America.

Until quite recently, however, the effect of altitude has not been studied at all closely nor exactly. At first sight it would appear that the indicated power of an engine should be proportional to the atmospheric density, but there are some features about the internal combustion engine which prevent advantage being taken of increased density when this is accompanied by low temperature.

Confining one's attention to aircraft engines, which in all cases use petrol as fuel, it is generally found that if the temperature of the induction pipe is allowed to reach too low a value the distribution between the various cylinders becomes bad and a serious loss of power occurs, accompanied by very irregular running. For this reason it is frequently arranged to heat the carburettors, induction pipes, or air intakes. Moreover, the mixture absorbs a considerable amount of heat from the cylinder walls, valves, and piston head during the induction stroke. The temperature of these parts and of any pre-heating arrangements, if fitted, bears no direct relationship to that of the surrounding atmosphere. The variation of power with altitude is therefore dependent to some extent on the particular design of engine. A fair amount of research on this subject has been carried out both in flight and on the bench. A paper on this subject[1] was written by Mr. D. H. Pinsent and Captain H. A. Renwick, who came to the conclusion, from a number of flight tests, that the power developed by aircraft engines was a function of the atmospheric pressure only, and almost independent of temperature. This, however, is not in very close agreement with bench tests. The following formula will generally give results with an error not exceeding 3 per cent or 4 per cent when used to determine the power developed up to 25,000 ft. altitude from tests on the ground:

$$W_2 = W_1 \frac{p_1}{p_2} \times \left(\frac{t_2}{t_1}\right)^{\cdot 4},$$

where W_1 and W_2 are the indicated horse-powers,

p_1 and p_2 the absolute atmospheric pressures,

and t_1 and t_2 the absolute atmospheric temperatures

during the test and under the required conditions.

With extreme designs the index, given as ·4, might be expected to vary between ·2 and ·7. To determine the brake horse-power, the assumption may be made that the mechanical losses are constant and, if unknown, may be taken as averaging about 12 per cent of the ground indicated horse-power.

Various arrangements have been suggested and experimented with for preventing or minimising the reduction of power at altitude. These depend on increasing the explosive charge in the cylinder by some auxiliary pumping device. Stepped pistons have been used by Mr. Ricardo in which the underside of the piston is used as an air-pump, which both assists in scavengering the exhaust during the exhaust stroke and pumps in an extra quantity of air into the cylinder at the end of the suction stroke. It is intended with this arrangement that by means of suitable valves the pumping side of the piston should be disconnected from the main cylinder until an altitude is reached at which the super-charging may be allowed to take place safely. As the arrangement stands the amount of extra power that can be obtained is not very great, but it has the advantage that, with the exception of suction valves, no extra working parts are required, and although the weight of the engine is increased by the use of stepped pistons, the particular type employed has certain definite mechanical advantages which go some way to compensate for this.

In order to maintain at high altitude anything approaching an absolute pressure in the cylinder at the beginning of the compression stroke, comparable with the normal ground atmospheric pressure, a piston pump of considerable volume displacement is necessary. A much lighter and more compact arrangement consists in using some form of rotary compressor. A great deal of experimental work has been done in this direction, using centrifugal blowers driven either by gearing from the engine or directly coupled to a turbine driven by the engine exhaust. These devices cannot be more than mentioned here; their

[1] "Variation of Engine Power with Height," *Reports and Memoranda*, No. 462, published by the Aeronautical Research Committee.

present state of development leaves much to be done, but there seems no question that the power of engines at altitudes of 20,000 ft. and over can be very greatly increased by their means, and with an additional weight which is comparatively small. It is worth noting that an altitude of over 33,000 ft. has been obtained in an aeroplane in the United States with an exhaust-driven turbine-blower installation.

§ (3) Effect on Fuel Consumption.—In an ideal engine the thermal efficiency is a function of the compression ratio and independent of the density of the working fluid. The economy of such an engine, therefore, would not be affected by altitude conditions. In actual practice a decrease in the density of the air has an influence on the rate of combustion and on the proportion of heat lost to the cylinder walls, which somewhat reduces the thermal efficiency. This reduction is not very great. It has been investigated experimentally, but only for particular cases, from which it would not be possible to draw general conclusions.

A more important reduction in economy occurs at altitude owing to mechanical losses. Experiment has shown that these losses are more or less constant and independent of the power developed by a particular engine. They therefore bear an increasing proportion to the power developed in the cylinders as this power is diminished by a reduction of the surrounding atmospheric pressure.

It is possible to increase the power developed at altitude and at the same time to reduce the fuel consumption by raising the compression ratio. This, however, entails a certain sacrifice of power at low altitudes. Too high a compression ratio causes detonation and pre-ignition, but it has been found by experiment, at any rate under the conditions which exist in internal combustion engine cylinders, that the temperature at which detonation occurs increases with a decrease of the absolute pressure; consequently it is possible to use, without any adverse effect, a higher compression ratio when running in an atmosphere of less than the normal pressure with a corresponding increase in economy. A series of tests were carried out at the Royal Aircraft Establishment by Dr. E. G. Ritchie.[1] The experiments showed that a compression ratio of 7·6 to 1 could be used, when running at an atmospheric pressure corresponding to an altitude of 11,000 ft. and over, with a considerable increase in economy over that obtained with the normal compression ratio of the engine (4·9 to 1). There are obviously, however, distinct limits to the usefulness of increasing the compression ratio. In order that a high compression engine may run at low altitudes it is necessary to reduce the absolute pressure in the cylinder. The simplest way of doing this is to use a throttle valve and not to attempt to make use of the full power of the engine at low altitudes. If this is done, however, the power which can be safely obtained at ground level is approximately equal to that which the engine will develop at the lowest altitude at which it may be safely run on full throttle. This is considerably less than would be obtained with the same engine with a normal compression ratio running at full throttle.

§ (4) Effect on Carburation.—It can be shown that if a simple carburettor (that is, one which has no moving parts) gives a constant mixture under all running conditions at any particular atmospheric pressure, it will give a mixture which becomes richer as the atmospheric pressure is reduced, so that the mixture strength is approximately inversely proportional to the square root of the atmospheric density. It is therefore necessary for carburettors to be fitted with some arrangement by which the mixture ratio can be adjusted either automatically or by hand.

The arrangements in general use in England consist either of an adjustable needle valve situated between the float chamber and the jet, or an adjustable air valve by which the space above the petrol in the float chamber can be connected both to the outside atmosphere and to the point of maximum depression in the choke tube of the carburettor. This latter arrangement has one important advantage, which has, however, generally not been made use of. If an engine be fitted with a number of carburettors, only one air valve will be required for all of them, as it can be connected by suitable pipes to their respective float chambers and choke tubes. When this is the case no question arises of synchronising controls on different carburettors. Unfortunately, in most cases, this has not been done and each carburettor has been fitted with its own valve. In this case this method would appear to have no advantage over the control by variable needle valve in the petrol supply. Various arrangements have been made to effect this compensation automatically. In one arrangement the air valve which interconnects the float chamber space and choke tube is actuated by a sealed aneroid diaphragm, while the connection to the atmosphere is under hand control. The tests so far carried out show that this arrangement works very satisfactorily, and that one setting of the hand control is correct for all heights. The apparatus has not, however, been tested above 15,000 ft.

[1] "The Effect of Compression Ratio on the Behaviour of an Aero Engine at Altitude," *Internal Combustion Engine Sub-Committee Reports*, No. 44, published by the Aeronautical Research Committee.

It has been proposed to construct a carburettor with a jet of peculiar form, so that the velocity of the petrol was such that the flow was purely viscous. In this case the rate of flow would be proportional to the pressure difference between the float chamber and the choke tube. Under these circumstances it can be shown that the rate of flow would be proportional to the absolute density of the atmosphere. Some experiments were actually carried out with a carburettor of this type, but apart from difficulties encountered which need not be detailed here, it would not appear possible for such a carburettor to give a constant mixture ratio with varying rates of air flow for any constant atmospheric condition without some form of compensating device, since it is impossible to reduce the air velocity to that corresponding to viscous flow.

The low temperatures existing at altitude have an adverse effect on the uniformity of the petrol mixture distributed to the various cylinders. The mixture formed by a carburettor consists of air-petrol vapour and finely divided liquid petrol. Wherever the latter touches the walls of the induction pipe it is apt to coalesce and form coarse streams of liquid, which may be distributed among the cylinders in very unequal proportions. It is therefore necessary to supply a certain amount of heat to the induction system to reduce the proportion of fuel coalescing on the walls of the induction pipe, in order to ensure reasonably good distribution. The best method of doing this, in the case of water-cooled engines, is to water-jacket the induction pipe. It is impossible to give a general estimate of the heat required, as this varies very greatly with the design of the induction system. In certain types of air-cooled engines in which the air intakes are exhaust heated, it has been found necessary to pre-heat the incoming air to such a degree that under no circumstances is its temperature less than $+3°$ C. In order to meet the conditions existing at 25,000 ft. this involved raising the temperature of the air 35° to 40° C. This may be regarded as an extreme case. As the addition of heat at this point in the cycle of operations is a disadvantage from every other point of view, no more heat should be supplied than is absolutely necessary.

§ (5) Effect on Electrical Ignition.—That altitude has any effect on electrical ignition is due to the fact that the apparatus used relies to a considerable extent on air as an insulator, and also to the peculiar nature of the arrangements made for protecting the apparatus from accidental excessive electrical strain. All that need be said about the first point is that any air gaps must be appreciably greater than are required at ground level in order to prevent the passage of a spark at altitude. With regard to the second point, all electrical ignition systems are protected by arranging a permanent spark-gap in parallel with the plugs, so that an excessive voltage, generated by the magneto or coil, such as might be caused by a broken sparking plug or high-tension lead, is prevented by providing an alternative path for the current across this spark-gap. It is essential, of course, that this gap should be sufficiently great to prevent the passage of a spark except under accidental circumstances such as mentioned above. The dielectric resistance across the safety gap decreases at altitude owing to the reduction in atmospheric pressure, but unfortunately the resistance across the sparking plug points does not decrease to the same extent, although the compression pressure is proportionally decreased. Trouble is therefore apt to be experienced at altitude by sparking occurring across the safety gap in preference to the plug points. The remedy is to construct the magneto or coil to withstand a higher voltage and to increase the resistance of the safety gap, or preferably to use some form of safety gap which has a constant dielectric resistance. Research is being carried out on safety gaps, but an entirely satisfactory method of maintaining a constant resistance has not yet been found.

§ (6) Effect on Cylinder Cooling.—Limitations of weight and head resistance necessitate the reduction of water radiators to the smallest possible dimensions. For any given indicated air-speed (that is, true air-speed divided by the square root of the atmospheric density) it is approximately true that the heat dissipated by a radiator is proportional to the mean difference of temperature between the radiator and the surrounding air, and is more or less independent of the air density; provided that, as is normally the case, the rise in temperature of the air passing through the radiator is small compared with the mean difference of temperature between the radiator and the air. The heat dissipated also increases with increase of air-speed, but not proportionately. For a constant engine speed the heat rejected to the cylinder water-jackets decreases as the power decreases, though not proportionally. Actual experience shows that in the case of aeroplanes the maximum water temperature is reached when climbing at maximum rate of climb, and occurs at a height of between 4000 and 6500 feet. The worst condition really occurs at sea-level, but owing to the considerable heat capacity of the water system the maximum temperature is not reached until the aeroplane has been flying for some little time. A radiator which is satisfactory under the conditions above is generally satisfactory under all other circumstances, including flying level at low altitudes at full speed. Owing to the low temperature of the atmosphere at high alti-

tude, there is no difficulty in keeping the water sufficiently cool to avoid trouble owing to the lower boiling-point of water due to the diminution in the atmospheric pressure. Indeed, it is essential that radiators should be fitted with shutters, or other suitable arrangements, in order that the water may be prevented from becoming too cold or even freezing when the engine is throttled down.

The remarks above apply also to airships, except that the worst condition occurs when flying low with only one or two engines working.

In air-cooled engines the same conditions apply, but in this case the benefit from the lower temperature at altitude is not so marked, owing to the much higher temperature difference between the cooling surfaces and the air.

§ (7) General Conclusions.—From a consideration of the various effects of altitude on the performance of aircraft engines, it will be seen that the most important is the decrease in power as the altitude is increased. It is worth noting that this decrease in the case of commercial aeroplanes is a positive advantage, owing to the fact that the maximum power is required when leaving the ground. When flying height has been obtained considerably less power is required, even though the aeroplane be flown level at a much higher speed. In this respect there is very little difference between aeroplanes of high and moderate performance. In the case of airships, the diminution of power is a disadvantage, since the power required is determined by the flying level conditions. Diminution in power obviously means increased weight of the power plant for a given performance, but this is not really very serious, as the weight of fuel is much more important than that of the engines, owing to the long endurance required in the case of airships.

Special plant for research on the effect of altitude conditions exists at the Royal Aircraft Establishment in England, at the Bureau of Standards, Washington, U.S.A., and on the Continent. At the R.A.E. an entirely new plant has been designed and its construction is now practically complete. This plant will be capable of imitating almost any possible conditions of atmospheric pressure and temperature which can occur, and will permit of the largest engines being tested under these conditions.

G. H. N.

Exposure to Weather, effect on textiles. See "Aeroplane Wings, Fabrics for," § (11).

— F —

Fin. See "Aeroplane, Component Parts of."

FLIGHT, PRINCIPLES OF

In all heavier-than-air craft the machine is sustained in the air by the excess pressures on the under side of its wings as it is propelled through the air.

Fig. 1 represents a section of a wing. As it moves forward it meets air at rest at C

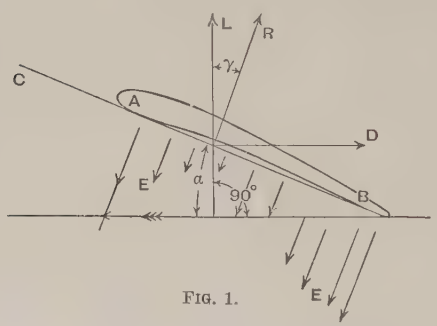

Fig. 1.

and leaves it with a downward momentum at E; the result of this is an upward force R acting through the centre of pressure of the wing. In the figure AB is the chord of the wing, and the angle α between AB and the direction of relative motion is known as the angle of attack.

Let R make an angle γ with a line at right angles to the direction of motion. We can resolve it into two components, D—the *Drag*—and L—the *Lift*—in and at right angles to this direction respectively, and we have

$$L = R \cos \gamma,$$
$$D = R \sin \gamma.$$

If the machine is moving horizontally at uniform speed the lift L must just balance its weight W, while the drag balances the propeller thrust T. In this case we have

$$R \cos \gamma = L = W,$$
$$R \sin \gamma = D = T.$$

To a high degree of accuracy the lift and the drag are both proportional to the area of the wing S, the square of the velocity of flight relative to the air V, and the density of the air [1] ρ. They also depend on the angle of attack. Thus we may write

$$L = k_l \rho S V^2,$$
$$D = k_d \rho S V^2,$$

where k_l and k_d, known respectively as the lift and drag coefficients, themselves depend on the angle α.

[1] See "Aircraft Model Experiments in Relation to Full Scale"; also "Aircraft, Performance of," § (3).

It can be shown,[1] by resolving along a perpendicular to the direction of motion, that if γ be the least angle to the horizon at which the aeroplane will glide to the ground with the engine shut off, then $\tan\gamma = D/L$, where D measures the total drag, acting opposite to the direction of motion, on the machine including wings and body, and L the lift which acts at right angles to the direction of motion. Substituting the values of L and D, we find

$$\tan\gamma = \frac{k_d}{k_l}.$$

Experiments in an air channel [2] on an aerofoil enable us to determine the values of the lift and drift for various angles of incidence, and we obtain curves such as that shown in *Fig.* 2, in which the coefficient k_l and the ratio k_l/k_d are plotted against the angle of attack.

We may use such curves to discuss the

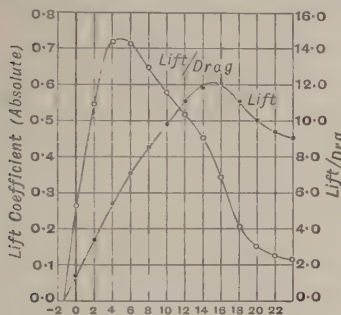

FIG. 2.

behaviour of the machine. Thus in *Fig.* 3 the curve ABCD represents the curve of lift of a certain aerofoil plotted against the angle of attack for a speed of 40 miles per hour.

This is an experimental curve. The other curves represent the lift for various other speeds and are found by taking ordinates in the ratio of the squares of the respective speeds. Thus the curve marked 60 m.p.h. is obtained from ABCD by increasing each ordinate in the ratio of $(60/40)^2$, multiplying them, that is, by 9/4, and so on. We are thus able to find the load the wing can carry at a given speed and given angle of attack, or, on the other hand, knowing the load the wing has to carry, we can find the requisite angle of attack corresponding to various speeds. Thus, if we assume the load to be 2000 lbs., we note that on the diagram the 2000-lb. line touches the curve for 40 m.p.h. at D, and cuts those for higher speeds at D_1, D_2, etc.; while the curve for 35 m.p.h. does not reach it.

Thus the machine could not leave the ground unless its speed was over 40 m.p.h.; in this case, assuming sufficient engine power, the angle of attack for speeds of 40 m.p.h. would be 17°·5. At 50 m.p.h. it would be rather less than 9°, and so on.

We can proceed from this to find the h.p.

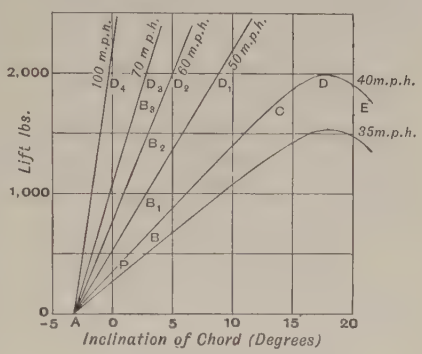

FIG. 3.

required to drive the aircraft at various speeds. *Fig.* 4 is a series of curves giving the relation between the resistance at various speeds and the angle of attack, or angle of incidence on the wings. Of these, ABCDE corresponding to 40 m.p.h. is obtained by direct wind-channel experiments; the others, as before, are found by varying the ordinates in the ratio of the square of the speeds. It will be noticed that

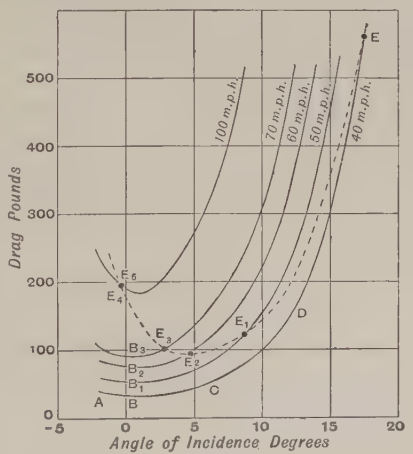

FIG. 4.

the curves all show a minimum in the neighbourhood of one or two degrees and then rise steeply as the incidence is increased.

We may use these to determine the resistance at various speeds of the aeroplane of weight 2000 lbs.

Thus at 40 m.p.h. we find from *Fig.* 3 that

[1] See Bairstow, *Applied Aerodynamics*, chap. ii. p. 35, from which the above figures are taken.

[2] See "Model Experiments in Aeronautics."

the angle of attack required for flight is 17°·5. An ordinate to *Fig.* 4 drawn at 17°·5 cuts the 40 m.p.h. curve at E, and the value of this ordinate is, we see from the figure, 560 lbs. Thus the resistance to the wing alone, moving at 40 m.p.h. and at the necessary angle of incidence, is 560 lbs.

For flight at 50 m.p.h. the incidence is about 9° and the corresponding ordinate cuts the 50 m.p.h. curve at E_1 corresponding to a resistance of 130 lbs. Proceeding in this way we get the curve EE_1E_2 . . . which gives the resistance to the wing at various speeds.

The resistance, we have seen, is given by the expression $k_d\rho V^2S$, where k_d depends on the angle of attack and falls as it is decreased. As the speed rises the value of V^2 increases, but at first—starting from 40 m.p.h.—the decrease in k_d more than balances the increase in V^2, and the curve of resistance falls rapidly, reaching a minimum at about 60 m.p.h. At higher speeds the effect of the increase in speed is such that the resistance again rises.

We may use these results to find the horse-power needed, for this is given by multiplying the resistance by the speed and assuming the resistance to be measured in lbs., the speed in feet per second—dividing the result by 550. It must be remembered, however, that the resistance must include that of the body, struts, engines, etc. ; the results obtained from *Fig.* 4 apply only to the wings. Now we may take the resistance at 40 m.p.h. to be 50 lbs. and may assume that at other speeds it varies approximately as the square of the speed ; while this is not strictly true, for the attitude of the machine will vary to some extent with the speed, the assumption is sufficient for the present. Thus at 60 m.p.h. the body resistance is 113 lbs., and so on.

Hence at 40 m.p.h. the total resistance is 560 + 50, or 610 lbs. ; at 60 m.p.h. it is 97 + 113, or 210 lbs.

Again, a speed of 1 m.p.h. is 1·47 ft. per sec., so the respective speeds are

$$40 \times 1{\cdot}47 \text{ and } 60 \times 1{\cdot}47 \text{ ft. per sec.}$$

Multiplying the resistances respectively by these figures and dividing by 550, we find for the h.p. the values 65 and 34 respectively.

Thus to drive the plane at 60 m.p.h. requires approximately half the power necessary to propel it at 40 m.p.h.

It must be remembered that these figures

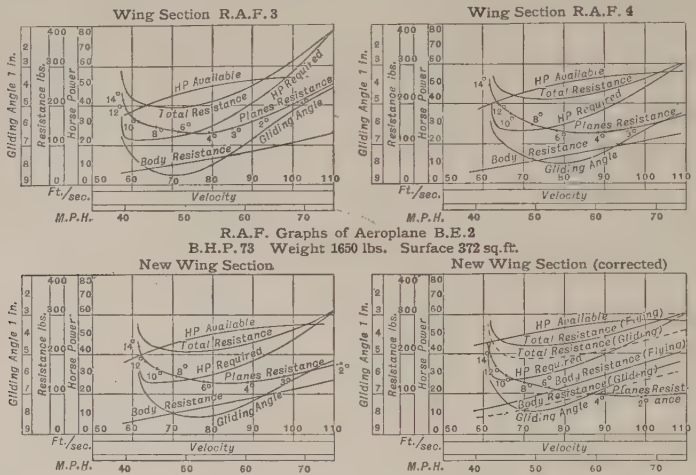

FIG. 5.

give the net horse-power delivered to the air and do not allow for engine and airscrew losses. To determine the brake horse-power at the engine we may assume a propeller efficiency of 60 per cent. Thus our h.p. figures require multiplying by 100/60, and become 108 and 57 respectively.

In a somewhat similar manner curves can be obtained giving the airscrew thrust in terms of revolutions—one of these will be experimental, the others deduced from it on suitable assumptions as to the relation between the thrust, the revolutions per minute, and the speed.[1] For these reference should be made to works dealing with aerodynamics. Tables can be prepared and curves drawn showing the power required for climbing, the effect of additional weight on speed, or the effect of height, of horse-power and airscrew revolutions.

Fig. 5 gives a number of curves which are

[1] See Bairstow, *Applied Aerodynamics*, chap. ii.

self-explanatory. They show for various speeds the horse-power available and the horse-power required for various conditions of flight; they give also the gliding angle, the resistance of the planes, and the body resistance under the same conditions.

Flight, Rectilinear Symmetrical: flight with no yaw or bank in steady motion, stability in. See "Aircraft, The Stability of," § (12).

Fluid Flow experiments in a water channel. See "Model Experiments in Aeronautics," § (2).

Flying Boat Hulls, strength tests on. See "Aeroplane Structures, Experiments," § (16).

Forced Oscillation Method of determining Rotary Derivatives for Aircraft Models. See "Model Experiments in Aeronautics," § (8) (iii.).

Fuselage. See "Aeroplane, Component Parts of."

Strength tests on, under down loads. See "Aeroplane Structures, Experiments," § (12).

Fuselage Frameworks, general construction of. See "Aeroplane Structures, Theory," § (2).

— G —

Gap. See "Aeroplane, Component Parts of."

Gelatine as a proofing for balloon fabrics. See "Diffusion through Membranes," § (15) (iii.).

Glides applied to a determination of the lift and drag of an aeroplane. See "Aerodynamic Research, Full Scale," § (12).

Gliding Angle. See "Flight, Principles of." Its tangent is equal to the ratio of the Drag to the Lift.

Gold-beater's Skin: a preparation from the intestines of cattle, used for rendering fabrics impermeable to gases. See "Diffusion through Membranes," § (15) (v.).

Gusts, effect of, on aircraft stability. See "Aircraft, The Stability of," § (15).

Gyro Turn Indicator: an instrument used on aircraft depending upon the precession of a gyro wheel to indicate deviation from a straight course. See "Aircraft, Instruments used in," § (4) (ii.).

Gyroscopic Methods of determining the Angular Elevation (or Depression) of Aircraft. See "Aircraft, Instruments used in," § (10) (iii.).

Gyroscopically Controlled Rudder: an automatic device by means of which an aeroplane is kept on a given course. See "Aircraft, Instruments used in," § (7).

— H —

Haze Horizon Method: a method of determining the angular elevation (or depression) of aircraft by regarding the top layer of atmospheric haze on the horizon. See "Aircraft, Instruments used in," § (10) (i.).

HELICOPTER, THE

The problem of the helicopter, that is, of an aerial machine supported in the air by the thrust of one or more airscrews rotating about the vertical, is not new and has interested many experimenters. At present there are two distinct types of helicopter—firstly, the machine which has an "aeroplane" body with tail-plane, landing gear, etc., but with which, instead of wings, the sustaining force is obtained from airscrews rotating about the vertical; and secondly, the machine which bears no resemblance whatever to an aeroplane. Whilst many helicopters have been constructed, only a few have supported in the air their own weight, and not one has been successful when judged from the standpoint of practical utility. In addition to sustentation, there are other problems—such as stability and controllability in the air, the assurance of a safe descent after a complete failure of the engine plant, and the attaining of a sufficiently high speed in the horizontal plane—which need consideration if the helicopter is to compare favourably with the modern aeroplane. At present very little is known about these important problems, so that much experimental research will be needed before the helicopter can be regarded as a commercial proposition. Obviously, a helicopter possesses the advantage of being able to ascend very rapidly from the ground or to land on a very small ground space so that an extensive aerodrome, a necessity for an aeroplane, is not needed. At the outset we shall consider the simple problem of the sustentation of a helicopter hovering in the air, that is, the problem of an airscrew designed to rotate at a stationary point. The problem

of stability and controllability will not be considered.

The usual method of presenting the performance of a helicopter is in terms of the absolute coefficients [1] T_c, Q_c, and P_c, where the thrust $T = T_c \rho n^2 D^4$, the torque $Q = Q_c \rho n^2 D^5$, and the power absorbed $P = P_c \rho n^3 D^5$. In these expressions the density ρ, the rotational speed n, the diameter D, as well as T, Q, and P are measured in any system of consistent units.

With any helicopter, an increase of the absorbed power is accompanied with an increase of rotational speed, so that since $T/P = (T_c/P_c) \times 1/nD$, it follows that the thrust per horse-power decreases. With similar helicopters absorbing the same power, P_c, T_c, and $\rho n^3 D^5$ are constants; thus $(nD)^3$ varies inversely as D^2, so that by making D sufficiently large the thrust per unit power, which varies as $(1/nD)$, may be increased without limit.

A helicopter which is merely sustaining a weight in the air is doing no useful work, so that the ordinary definition of efficiency is inadequate as a criterion of value. It is desirable, however, from consideration of blade strength and the gear reduction ratio of the engine, that the diameter should be small and the rotational speed large, so that the best helicopter for a given power would be the one which develops the largest thrust with the minimum diameter and the largest rotational speed.

From the previous expressions it can readily be seen that

$$P = P_c \cdot \rho \cdot \left(\frac{T_c}{P_c}\right)^3 \cdot \left(\frac{P}{T}\right)^3 \cdot D^2,$$

that is,

$$T^3 = P_c \cdot \rho \cdot \left(\frac{T_c}{P_c}\right)^3 \cdot P^2 \cdot D^2,$$

where $P_c \cdot \rho \cdot (T_c/P_c)^3$ is a constant for geometrically similar helicopters. It follows, then, that when comparing different helicopters, the larger the value of $T_c \cdot (T_c/P_c)^2$ the larger will be the thrust which may be developed with given values of the power and the diameter, or the smaller the diameter to develop a given thrust from a given power. Further, since

$$P = P_c \cdot \rho \cdot (nD)^5/n^3 = P_c \cdot \rho \cdot \left(\frac{T_c}{P_c}\right)^5 \left(\frac{P}{T}\right)^5 \times \frac{1}{n^2},$$

that is,

$$T^5 = \rho \cdot T_c \cdot \left(\frac{T_c}{P_c}\right)^4 \cdot \frac{P^4}{n^2},$$

the larger the value of $T_c \cdot (T_c/P_c)^4$ the larger will be the thrust developed at given values of the power and rotational speed, or the larger will be the rotational speed necessary to develop a given thrust at a given power. The factors $T_c \cdot (T_c/P_c)^2$ and $T_c \cdot (T_c/P_c)^4$ may therefore be regarded as the criteria of the performance of a helicopter, since the greater the values of these factors the smaller will be the diameter and the larger will be the rotational speed necessary to develop a given thrust from a given power. This may perhaps be made clearer from the data of the following table, in which a comparison is made of the performances of two helicopters "A" and "B." Each helicopter was designed to develop a thrust of 3500 lbs. when absorbing 120 horse-power at ground level ($\rho = 0{\cdot}00237$ slugs per cubic ft.).

	Helicopter A.	Helicopter B.
Measured value of T_c	0·040	0·125
Measured value of P_c. [$P_c = 2\pi Q_c$]	0·0125	0·050
Value of (T_c/P_c)	3·20	2·50
Value of $T_c \cdot [T_c/P_c]^2$	0·41	0·78
Value of $T_c \cdot [T_c/P_c]^4$	4·20	4·90
Value of nD [ft./sec.]	60·2	47·1
Value of n (r.p.m.)	35·8	38·7
Value of D (feet)	101 0	73·0

It will be noticed that helicopter "B" is much better than helicopter "A," since it develops the same thrust per unit power with a much smaller diameter, 73 ft. as compared with 101 ft., and at a slightly larger rotational speed. Attention is particularly directed to the fact that the real criteria of performance are the two factors $T_c \cdot (T_c/P_c)^2$ and $T_c \cdot (T_c/P_c)^4$, which are both larger for helicopter "B," and not the factor (T_c/P_c) which has the larger value for the helicopter "A."

Although very little experimental work has been made on helicopters, there is very good reason to believe that the best possible values of $T_c \cdot (T_c/P_c)^2$ and $T_c \cdot (T_c/P_c)^4$ are about 0·80 and 4·65 respectively, the corresponding values of (T_c/P_c), T_c, and P_c being 2·40, 0·140, and 0·0585 respectively. With such a helicopter the blade angle at the working part of the blade would be about 8° or 9° with a two-blader and about 10° or 11° with a four-blader, the difference of angle being due to the larger inflow velocity in the case of the four-blader. At these blade angles the pitch-diameter ratio of the helicopter is about 0·50.

At the present time there is no thoroughly reliable theory of the helicopter, so that it is extremely difficult to estimate the magnitude and the distribution of inflow velocity along the blade.

Assuming the Froude conception to be directly applicable to the case of a helicopter, it can be easily shown that $T/P = \sqrt{(\pi \cdot D^2 \cdot \rho/2T)}$. The assumptions of Froude are not, however, directly applicable to practice, so that it is

[1] For an explanation of these terms see "Airscrew, The," § (4).

necessary to introduce a factor K_f in the previous expression, such that $T/P = K_f\sqrt{(\pi \cdot D^2 \cdot \rho/2T)}$. This absolute coefficient K_f may be regarded as a criterion of performance in that it is a numerical measure of the extent to which the actual performance approaches that of the helicopter working under ideal conditions. In fact, since $T = T_c \cdot \rho n^2 D^4$ and $P = P_c \cdot \rho n^3 D^5$, it follows that $K_f = \sqrt{(2/\pi \cdot T_c^3/P_c^2)}$, so that $(\pi \cdot K_f^2/2)$ is the same as the standard criterion of performance, namely, $T_c \cdot (T_c/P_c)^2$.

It may be assumed, unless shock absorbers of considerable size are mounted, that the speed of descent must be kept within 16 ft. per sec., so that the safety of a helicopter during a forced descent with the engine off needs consideration. There would appear to be three methods by which in the case of engine failure the speed of vertical ascent may be kept under control.

(*a*) Preventing the helicopter from rotating and relying upon the "parachute" effect of the stationary blades. The method is only effective when the blades have a very large area.

(*b*) To allow the helicopter to rotate freely as a "windmill," when the direction of rotation would be opposite to that of the drive. Also, the helicopter will then rotate at the rotational speed, which, combined with the speed of descent, makes the windmill torque equal and opposite to the frictional torque of the engine, or equal to zero if the connection between engine and helicopter be broken. In such a case the resistance of the "windmill" is small, largely because of the low aerodynamic efficiency of a blade which is moving in the direction of its trailing edge, which means if the condition of the equilibrium of torque is to be satisfied, that the component of the lift in the vertical direction is small.

(*c*) The third and best method is to rotate the blades so as to decrease the blade angle, so that the helicopter spins round as a windmill but in the same direction as when developing a thrust. The best angle of the blade will probably be in the neighbourhood of about $+1°$ or $-1°$, the latter angle being necessary if the windmill is dragging round the engine. It follows that in a descent with uniform velocity the windmill resistance is equal to the weight, so that such a helicopter should be designed to have the thrust when hovering equal to the "windmill" resistance of a descent with a uniform velocity.

In practice a helicopter should be able to work in strong head winds and also to advance in a horizontal plane. Methods of horizontal propulsion, frequently suggested, are either to incline the vertical axis so as to get a component of the thrust in the direction of the horizontal or to use subsidiary airscrews rotating about a horizontal axis. At present our knowledge of helicopters derived from experimental investigation is small, and much requires to be done.

A. F.

HELIUM, ITS PRODUCTION AND USES

§ (1) Introduction.—Shortly after the commencement of the war in 1914, it became evident that if helium were available in sufficient quantities to replace hydrogen in naval and military airships the risk of loss in life and equipment would be very greatly lessened.

The fact that helium is both non-inflammable, non-explosive, and possesses 92 per cent of the lifting power of hydrogen, makes it a most suitable filling for airship envelopes. By the use of helium, the engines of airships can be placed within the envelope if desired. A further advantage possessed by helium over hydrogen is that the buoyancy may be increased or decreased at will by heating and cooling the gas by electric or other means, which fact may possibly lead to considerable modifications in the technique of airship manœuvring and navigation. Moreover, the loss of gas from diffusion through the envelope is less with helium than with hydrogen to the extent of about 30 per cent.

It was known that there existed in Canada and in the United States of America large supplies of natural gas containing helium in varying amounts, and Sir Richard Threlfall, K.B.E., in 1915 proposed to the Board of Inventions and Research of the British Admiralty that it should take steps to develop a method of extracting this helium on an industrial scale. Preliminary calculations made by him led to the belief that there was substantial ground for thinking that helium could be obtained in large quantities from these sources at a cost which would not be prohibitive for its use in aeronautics.

In the autumn of 1915 Professor McLennan of the University of Toronto was invited by the Board of Inventions and Research to determine the helium content of the supplies of natural gas in Canada, and later on of those within the Empire, to carry out a series of experiments on a semi-commercial scale with the helium supplies which were available, and also to work out all technical details in connection with the production of helium in quantity, as well as those relating to its repurification.

§ (2) Sources and Supply of Helium.—In commencing the investigation, a survey was made of all the natural gases available in larger or smaller quantities within the Empire, and the natural gases in Ontario and in Alberta, Canada, were found to be the richest in helium. Although these gases contained but 0·33 per cent of helium, it was found that

they could supply in the aggregate from 10,000,000 to 12,000,000 cubic feet per year.

§ (3) Method of extracting Helium.—Several methods of extracting the helium were investigated, but in the one which proved successful it was found that the helium could be most readily and economically extracted by producing the refrigeration necessary to liquefy all the gases except the helium by the cold obtainable from the natural gas itself.

The machine as finally designed for the production of helium of approximately 97 per cent purity is shown in diagram in *Fig.* 1. It conforms on general lines to the standard oxygen-nitrogen machine of L'Air Liquide Société. It consists of:

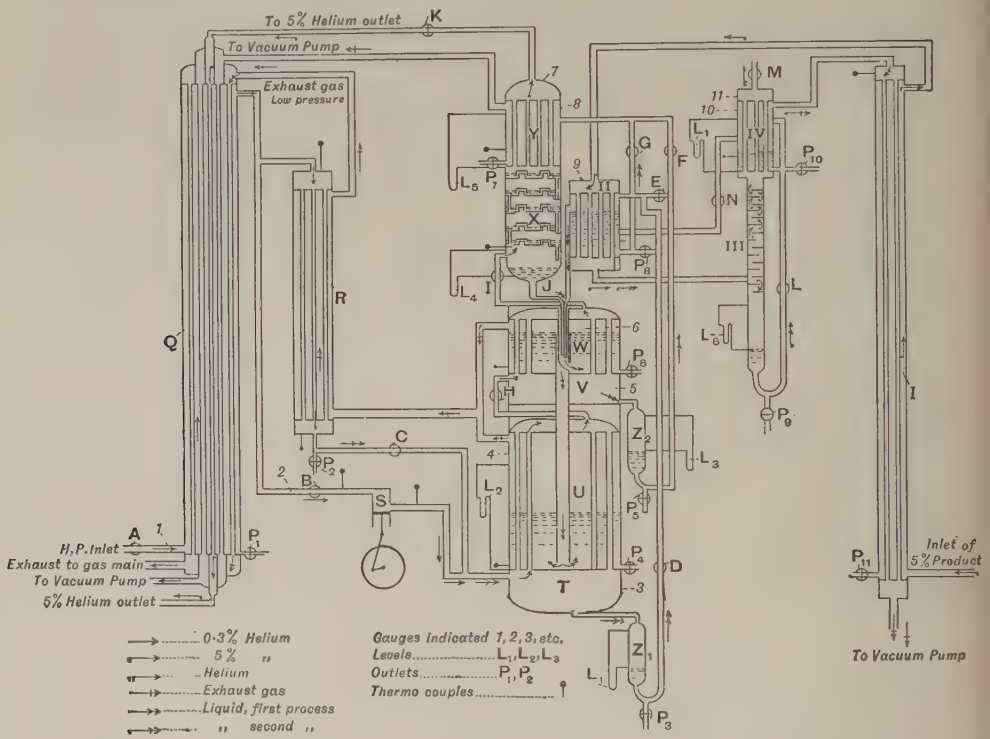

Fig. 1.

1. Two exchangers of temperature, one of which, Q, is shown, the two being so arranged that the flow of gas through them can be reversed, as is the present practice in the oxygen and nitrogen machines. The high-pressure gas is in the outer casing, and the return low-pressure gas in the small tubes; the heads are provided with three sections, so that the low temperature of the outgoing gases can be utilised.

2. A liquefier R. This is the same as the liquefier in the standard machines, but it has only one of the returning gases flowing through it.

3. An expansion engine S. This engine is of the standard type used in the oxygen and nitrogen machines.

4. A first vaporiser and pot U, T. This vaporiser, with pot for collecting liquid, is the same as on the standard nitrogen column.

5. A second vaporiser and pot W, V. This vaporiser, with the pot, is similar to the second vaporiser now used on the standard nitrogen columns. It should be about one-third the size of the first vaporiser U.

6. A rectification column X. This column should stand a pressure of 10 atmospheres and have a collecting basin at the bottom. Its diameter should be about three-eighths of that of the vaporisers U or W. Its length should not exceed 2 feet.

7. A vaporiser Y. The diameter of this vaporiser is the same as that of the rectification column X, and its length should not exceed 2 feet. On this vaporiser a partial vacuum is maintained.

8. Two collecting bottles Z_1, Z_2.

9. Two exchangers of temperatures, one of which, I., is shown. These are similar to

Q, and should be reversible, but their capacity is only 6 per cent of Q.

10. A vaporiser II. This vaporiser should be of the same size as Y, and the high-pressure side of it should stand a pressure of 50 atmospheres.

11. A rectification column III. This column should stand a pressure of 50 atmospheres, and should be about half the diameter of the column X and about 3 feet long.

12. A vaporiser IV. This should be similar to vaporiser II., but only half the diameter; on this vaporiser a partial vacuum is maintained.

13. The control valves are designated by letters from A to N, fourteen in all.

14. The outlets are designated by P_1, P_2, etc., eleven in all.

15. The gauges are designated by the numbers in italics, thus *1*, *2*, etc., eleven in all.

16. The levels for showing the depth of liquid are designated by L_1, L_2, etc., seven in all.

17. The method of connecting up is shown in the figure. The method of using the column is as follows:

(i.) *The First Process.*—(*a*) The compressed gas enters the exchangers Q through valve A, and, after passing out of the exchanger at the top, some of it goes through the liquefier R, and the rest of it through the expansion engine S to the first pot T. In T the pressure is about 4 atmospheres, and most of the gas is liquefied in the condenser U. The uncondensed part passes through the valve H into V, where more of it is liquefied in the condenser W. The still uncondensed gas flows through valve L to the bottom of the rectification column X; it passes up through the column, through the condenser Y, where more of it is liquefied, and the rest, which now contains about 5 per cent of helium, passes through valve K, where the pressure is reduced to nearly atmospheric, and it passes through the inner section of the exchanger to a gasometer.

(*b*) The liquid that collects in the pots T and V is drained into the bottles Z_1 and Z_2, which are made fairly long, and the bottom limbs of the levels are about 6 inches from the bottom, so that it is possible always to keep liquid in the bottom of the bottles and prevent any uncondensed gas escaping. The liquids from the bottles Z_1 and Z_2 are passed through the valves D and E respectively into the vaporiser II.; in addition, the liquid from Z_2 can also be run into the vaporiser Y through valve F. The liquid in the vaporiser II. overflows into the vaporiser W, and it overflows from W into the first vaporiser U. Some of the liquid in the vaporiser II. can be passed through the valve into Y. Liquid that condenses in Y flows down through the rectification trays in X, and is passed through the valve J into the vaporiser W.

(*c*) The gases from the evaporating liquids in the vaporisers U and W pass directly back to the liquefier R, and from the liquefier to the exchanger Q, as shown in the diagram. The gas evaporated in vaporiser II. flows with the liquid down into vaporiser W. The gas evaporating under vacuum in vaporiser Y passes out through the exchanger Q to the vacuum pump.

(ii.) *The Second Process.*—(*d*) The gas containing helium drawn off in the first process through the valve K is recompressed to 30 atmospheres, and passes through the exchanger I. to the top of the condenser II.; it flows down through II., where part of it is liquefied, and the liquid and gas pass into the rectification trays III., to the collector at the bottom, the gas passing up through the column to the condenser IV., where the rest of the nitrogen is condensed, and the product, containing about 97 per cent of helium, is drawn off through the valve M. The vaporiser IV. is supplied with liquid through the valve Z from the collector at the bottom of the rectifying column III. It may also be supplied with liquid from the vaporiser II. through the valve N.

§ (4) Cost of Production.—Carefully prepared estimates show that a commercial plant suitable for treating the whole of the gas supply of a large field such as that in Alberta, Canada, would probably cost not more than £150,000. The amount of helium of upwards of 97 per cent purity obtainable per year from the field would be about 10,500,000 cubic feet. As to the operating costs, experience has shown that allowing for interest on the investment, a ten years' amortisation, salaries, supplies and running charges, helium can be produced in the Alberta field for considerably less than £10 per 1000 cubic feet. This sum does not, of course, include the cost of purchasing cylinders or of transporting them from and to the works, neither does it include any compensation to the owners of the field for the supply of gas.

§ (5) The Uses of Helium.—The investigation into the problem of producing helium in large quantities was originally undertaken with a view to the utilisation of the gas in aeronautical warfare. The investigation has shown that it can be produced at a cost which is not excessive, but it has also been shown that from the sources in the Empire which are known and have been examined, the supply of helium cannot be greater than about 12,000,000 cubic feet per year. This quantity clearly would be sufficient to keep only a very few of our airships of the larger type in commission, even if the gas were diluted to the extent of 15 per cent with hydrogen.

This amount would, however, suffice to keep a number of the smaller aircraft supplied. Moreover, it might be used to fill fireproof compartments adjacent to the engines if it were ever decided to instal these within the envelopes of our larger airships.

Since it has been demonstrated that helium can be produced in quantity, one is led naturally to consider in what directions one can hope to use the gas other than that originally intended. In industry it may be used as a filling for thermionic amplifying and oscillating valves. It may also be used for filling tungsten incandescent filament lamps, especially for signalling purposes where rapid dimming is an essential, and for producing gas arc lamps in which tungsten terminals are used, as in the "Pointolite" type. As regards illumination, helium arc lamps possess an advantage over mercury arc lamps in that the radiation emitted has strong intensities in the red and yellow portion of the spectrum.

It has been shown by Nutting (*Electrician*, March 1912) that Geissler tubes filled with helium are eminently suitable, under certain conditions, for light standards in spectrophotometry, but the amount of the gas which could be used in this way is very small.

In spectroscopy, especially for investigations in the ultra-violet region, helium is invaluable. Doubtless its use in this field will be rapidly extended. The use of the gas in physical laboratories generally, and especially where certain investigations on the properties of matter are carried out, will also be greatly increased.

It has recently been proposed to use helium in place of oil for surrounding transformers and the switches and circuit-breakers of high-tension electric transmission lines. If the gas should prove suitable for this purpose, large quantities could be utilised, but it has yet to be demonstrated (and it is not clear that it can be) that in this field helium possesses any advantage over the oils now used.

It has been suggested by Elihu Thomson and others that if divers were supplied with a mixture of oxygen and helium, the rate of expulsion of carbon dioxide from the lungs might be increased, and the period of submergence as a consequence be considerably lengthened.

Another direction in which there is promise that helium may be used with advantage is in the synthetic production of such compounds as ammonia, nitric oxide, etc. It is known that the radiation from an arc in helium is exceedingly rich in the shorter light waves. If, therefore, mixtures of simple gases such as hydrogen and nitrogen or nitrogen and oxygen are exposed to this radiation, it is highly probable that a union of these gases can be economically effected.

In the field of low temperature research, however, it is probable that helium will immediately find its widest application. For this work helium is unique in that, when liquefied and possibly solidified, it enables one to reach the lowest temperature attainable.

J. C. McL.

HORSE-POWER AVAILABLE AND HORSE-POWER REQUIRED: relation between, shown by curves. See "Flight, Principles of."

HORSE-POWER NECESSARY TO PROPEL AN AEROPLANE AT VARIOUS SPEEDS. See "Flight, Principles of."

HUMIDITY, effect on weight of fabrics. See "Aeroplane Wings, Fabrics for," § (3) (ii.).
Effect on strength of fabrics. See *ibid.* §§ (6) (iii.) and (7).
For methods of measuring see "Humidity," Vol. III.

HYDRODYNAMICS IN ITS APPLICATIONS TO AERONAUTICS

§ (1) ANALYSIS OF FLUID MOTION.—It is shown in treatises on Hydrodynamics [1] that if u, v, w be the velocities at the point xyz of a fluid, $u+\bar{u}$, $v+\bar{v}$, $w+\bar{w}$ at a neighbouring point $x+\bar{x}$, $y+\bar{y}$, $z+\bar{z}$, then

$$\bar{u}=\frac{du}{dx}\bar{x}+\frac{du}{dy}\bar{y}+\frac{du}{dz}\bar{z}, \text{ etc.},$$

whence

$$\left.\begin{aligned}\bar{u}&=a\bar{x}+h\bar{y}+g\bar{z}+\eta\bar{z}-\zeta\bar{y}\\ \bar{v}&=h\bar{x}+b\bar{y}+f\bar{z}+\zeta\bar{x}-\xi\bar{z}\\ \bar{w}&=g\bar{x}+f\bar{y}+c\bar{z}+\xi\bar{y}-\eta\bar{x}\end{aligned}\right\}, \quad . \quad . \quad (1)$$

where

$$\left.\begin{aligned}f=\tfrac{1}{2}\left(\frac{dw}{dy}+\frac{dv}{dz}\right),\quad g=\tfrac{1}{2}\left(\frac{du}{dz}+\frac{dw}{dx}\right),\quad h=\tfrac{1}{2}\left(\frac{dv}{dx}+\frac{du}{dy}\right);\\ \xi=\tfrac{1}{2}\left(\frac{dw}{dy}-\frac{dv}{dz}\right),\quad \eta=\tfrac{1}{2}\left(\frac{du}{dz}-\frac{dw}{dx}\right),\quad \zeta=\tfrac{1}{2}\left(\frac{dv}{dx}-\frac{du}{dy}\right)\end{aligned}\right\}. \quad (2)$$

The first three terms in each component represent a velocity normal to the ellipsoid

$$a\bar{x}^2+b\bar{y}^2+c\bar{z}^2+2f\bar{y}\bar{z}+2g\bar{z}\bar{x}+2h\bar{x}\bar{y}=1,$$

while the last three represent rotation about the axes with angular velocities ξ, η, ζ respectively.

[1] See Lamb, *Hydrodynamics*, § 31; Stokes, "On the Theories of the Internal Friction of Fluid in Motion," *Camb. Phil. Trans.* (1845) viii.; *Math. and Phys. Papers*, i. 80. The Editor is indebted to Dr. Lamb for permission to make use of some of the articles in his treatise.

In the case of stream-line [1] motion we have

$$u=-\frac{d\phi}{dx},\quad v=-\frac{d\phi}{dy},\quad w=-\frac{d\phi}{dz}.$$

Thus
$$\frac{dw}{dy}=-\frac{d^2\phi}{dydz}=\frac{dv}{dz},$$

and the angular velocities ξ, η, ζ all vanish.

The equations of motion, employing the same notation, may be written

$$\left.\begin{aligned}\frac{Du}{Dt}&=\frac{du}{dt}+u\frac{du}{dx}+v\frac{du}{dy}+w\frac{du}{dz}=X-\frac{1}{\rho}\frac{dp}{dx}\\ \frac{Dv}{Dt}&=\frac{dv}{dt}+u\frac{dv}{dx}+v\frac{dv}{dy}+w\frac{dv}{dz}=Y-\frac{1}{\rho}\frac{dp}{dy}\\ \frac{Dw}{Dt}&=\frac{dw}{dt}+u\frac{dw}{dx}+v\frac{dw}{dy}+w\frac{dw}{dz}=Z-\frac{1}{\rho}\frac{dp}{dz}\end{aligned}\right\},\quad(3)$$

$$\frac{d\rho}{dt}+\frac{d\rho u}{dx}+\frac{d\rho v}{dy}+\frac{d\rho w}{dz}=0,\quad\ldots\quad(4)$$

where X, Y, Z are the components of the extraneous forces acting per unit of mass, p the pressure, and ρ the density. If the density is a constant the last equation becomes

$$\frac{du}{dx}+\frac{dv}{dy}+\frac{dw}{dz}=0.\quad\ldots\quad(4')$$

For stream-line motion, since $du/dy=dv/dx$ and $du/dz=dw/dx$, the first of equations (3) may be written putting Ω for the potential of the impressed forces,

$$-\frac{d}{dx}\frac{d\phi}{dt}+u\frac{du}{dx}+v\frac{dv}{dx}+w\frac{dw}{dx}=-\frac{d\Omega}{dx}-\frac{1}{\rho}\frac{dp}{dx},$$

with two similar equations.

Multiply these by dx, dy, dz respectively, and add; then the result can be integrated and leads to

$$\frac{dp}{\rho}=\frac{d\phi}{dt}-\Omega-\tfrac{1}{2}q^2+\mathrm{F}(t),\quad\ldots\quad(5)$$

where q^2 is written $(u^2+v^2+w^2)$, the square of the resultant velocity, and $\mathrm{F}(t)$ a function of t.

§ (2) Steady Motion.—When the motion is steady, so that the velocity at any point is no longer a function of the time but depends only on the position of the point, $d\phi/dt$ vanishes and $\mathrm{F}(t)$ becomes a constant c, thus we are led to the pressure equation

$$\int\frac{dp}{\rho}=-\Omega-\tfrac{1}{2}q^2+c.\quad\ldots\quad(1)$$

In the problems with which we have to deal in Aerodynamics it is possible to treat the air as of constant density, so that the left-hand side becomes p/ρ, while gravity is usually the only impressed force, and for Ω we may write gz, where z is the height of the point considered above some fixed plane. We thus obtain

$$\frac{p}{\rho}+\tfrac{1}{2}q^2+gz=\text{constant}.\quad\ldots\quad(2)$$

[1] See "Stream-line Motion," Vol. I.

§ (3) Circulation.—The value of the integral $q\,ds$, which is equal to

$$\int\left(u\frac{dx}{ds}+v\frac{dy}{ds}+w\frac{dz}{ds}\right)ds$$

taken along any line s in the fluid, is known as the "flow" of the fluid. If the ends of the line coincide so that the flow is taken round a closed curve, the flow becomes the circulation round the circuit bounded by s. We may find the circulation round any small circuit surrounding a point x, y, z, thus:

If $x+\bar{x}$, $y+\bar{y}$, $z+\bar{z}$ be a point on the circuit, then

$$\left.\begin{aligned}\bar{u}d\bar{x}+\bar{v}d\bar{y}+\bar{w}d\bar{z}=&\tfrac{1}{2}d(a\bar{x}^2+b\bar{y}^2+c\bar{z}^2+2f\bar{y}\bar{z}\\ &+2g\bar{z}\bar{x}+2h\bar{x}\bar{y})+\xi(\bar{y}d\bar{z}-\bar{z}d\bar{y})\\ &+\eta(\bar{z}d\bar{x}-\bar{x}d\bar{z})+\zeta(\bar{x}d\bar{y}-\bar{y}d\bar{x})\end{aligned}\right\}.\quad(1)$$

Thus, if we integrate round the boundary of the small area dS, we have

$$\left.\begin{aligned}\text{Circulation round } d\mathrm{S}=&\int\bar{u}d\bar{x}+\bar{v}d\bar{y}+\bar{w}d\bar{z}\\ =&\xi\int(\bar{y}d\bar{z}-\bar{z}d\bar{y})+\eta\int(\bar{z}d\bar{x}-\bar{x}d\bar{z})\\ &+\zeta\int(\bar{x}d\bar{y}-\bar{y}d\bar{x})\end{aligned}\right\}.\quad(2)$$

Now, remembering that the positive direction of integration is from x to y, y to z, and z to x, we see that $\int\bar{y}dz$ and $-\int\bar{z}dy$ are each equal to the projection of dS on the plane $x=0$; if l, m, n be the direction cosines of the normal to dS, each of these projections is equal to $l d$S; thus the right-hand side of the above equation is equal to

$$2(l\xi+m\eta+n\zeta)d\mathrm{S}.$$

The expression in the bracket is the angular velocity about the normal to the element, and we arrive at the result that the circulation round any element is equal to twice the product of the angular velocity about the normal to the element and the area of the element.

Again, we may divide any finite surface, as in *Fig.* 1, by a double series of lines crossing it, and apply the above theorem to each of the elementary areas thus formed. If we integrate the result over the whole finite area the flow on each side common to two elements comes in twice with opposite signs and disappears from the result, and we are left only with the flows in those sides which form part of the original boundary. Thus we have the result

Fig. 1.

$$\iint(udx+vdy+wdz)=2\iint(l\xi+m\eta+n\zeta)d\mathrm{S},$$

the single integral being taken round the boundary and the double integral over the surface of the area S.

§ (4) Rate of Change of the Circulation.—To obtain this we require to find the value of

$$\frac{D}{Dt}\int(udx+vdy+wdz),$$

where D/Dt stands for the complete differential coefficient

$$\frac{d}{dt}+u\frac{d}{dx}+v\frac{d}{dy}+w\frac{d}{dz}.$$

Now $$\frac{D}{Dt}(u\delta x)=\frac{Du}{Dt}\delta x+u\frac{D\delta x}{Dt}.$$

$D\delta x/Dt$ is equal to the rate of increase of δx and this is δu, while the equations of motion give us a value for Du/Dt in the form

$$\frac{Du}{Dt}=X-\frac{1}{\rho}\frac{dp}{dx},$$

where X is the impressed force parallel to the axis of x. Thus we find

$$\frac{D}{Dt}(u\delta x+v\delta y+w\delta z)$$
$$=-\frac{dp}{\rho}-\delta\Omega+u\delta u+v\delta v+w\delta w.$$

Thus

$$\frac{D}{Dt}\int_A^B(udx+vdy+wdz)=\left[-\int\frac{dp}{\rho}-\Omega+\tfrac{1}{2}q^2\right]_A^B. \quad (1)$$

Hence if Ω be single valued and A and B coincide, the integration being taken round a closed curve, the value of the right-hand side is zero, and we have

$$\frac{D}{Dt}\int(udx+vdy+wdz)=0, \quad . \quad . \quad (2)$$

or the circulation round any circuit moving with the fluid does not alter with the time.

Hence if at any time any portion of the fluid is moving irrotationally it will always retain this property.

§ (5) Vortex Lines and Tubes.—A line whose tangent always coincides with the axis of rotation of an element of the fluid is known as a vortex line. If $\xi\ \eta\ \zeta$ be the components of the angular velocity, the equation to the vortex line through the point x, y, z is

$$\frac{dx}{\xi}=\frac{dy}{\eta}=\frac{dz}{\zeta}. \quad . \quad . \quad . \quad (1)$$

Imagine that vortex lines are drawn through every point of the boundary of a small closed area in the fluid; the lines form a tube known as a vortex tube, or more simply as a vortex. Let ABC, A′B′C′ (*Fig.* 2) be two circuits drawn on the surface of a vortex tube and embracing it, and let AA′ be a line also drawn on the surface of the tube, and consider the circulation round the circuit ABCAA′C′B′A′A. It is equal to the value of

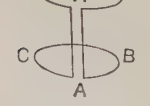

Fig. 2.

$\iint(l\xi+m\eta+n\zeta)dS$. But since the vortex lines lie in the surface, the angular velocity about a normal to the surface is everywhere zero. Thus

$$l\xi+m\eta+n\zeta=0,$$

and $$\int(udx+vdy+wdz)=0.$$

Hence, denoting the circulation round a circuit ABCA by I(ABCA), we have

$$\mathrm{I(ABCA)}+\mathrm{I(AA')}+\mathrm{I(A'C'B'A')}+\mathrm{I(A'A)}=0.$$

But $$\mathrm{I(AA')}+\mathrm{I(A'A)}=0.$$

Thus $$\mathrm{I(ABCA)}=\mathrm{I(A'B'C'A')}, \quad . \quad . \quad (2)$$

or the circulation round any circuit embracing a vortex tube is the same. The circulation round any small circuit embracing the tube is, we have seen, equal to $2\omega\sigma$, where ω is the resultant angular velocity given by $(\xi^2+\eta^2+\zeta^2)^{\frac{1}{2}}$ and σ the small area of the tube. Thus the product of the cross section of a vortex tube and the angular velocity is a constant; this product is called the strength of the tube, and the circulation is twice the strength of the tube. Hence a vortex line cannot begin or end in a fluid; it must form a closed curve or be continued to the boundaries of the fluid.

§ (6) To find the Velocity of the Fluid due to a given Distribution[1] of Vortices.—We treat the fluid as incompressible, and for our present purpose it will be sufficient to assume[2] that the vortices are straight and of constant strength k, say. We take the axis of y as parallel to the vortices; the motion will clearly be the same in all planes at right angles to this line, so that we shall have u, v, and w independent of y.

Since ζ and ξ are zero,

$$\frac{dw}{dy}=\frac{dv}{dz}=0,$$

$$\frac{du}{dy}=\frac{dv}{dx}=0.$$

Thus v is a constant, and since the motion is to vanish at infinity this constant must be zero; the motion is entirely in planes perpendicular to the axis of y.

Again we have the equations

$$\left.\begin{aligned}\frac{du}{dz}-\frac{dw}{dx}&=2\eta\\ \text{and}\qquad\qquad\\ \frac{du}{dx}+\frac{dw}{dz}&=0\end{aligned}\right\}. \quad . \quad . \quad . \quad . \quad (1)$$

The last equation is satisfied if we put

$$u=-\frac{d\mathrm{G}}{dz},\quad w=\frac{d\mathrm{G}}{dx}, \quad . \quad . \quad (2)$$

[1] It is assumed that the angular velocities all vanish beyond some finite distance from the origin.

[2] For a more general discussion see Lamb, *Hydrodynamics*, § 145.

and the first equation becomes

$$\frac{d^2G}{dx^2}+\frac{d^2G}{dz^2}=2\eta.$$

Thus, remembering that $d^2G/dy^2=0$, we see that G is the potential[1] of matter distributed throughout space with density $\eta/2\pi$.

Hence if $dx'dy'dz'$ be an element of volume at a point where the angular velocity is η', and r the distance between this point and the point x, y, z at which u and v are to be found,

$$G=\frac{1}{2\pi}\iiint\frac{\eta'}{r}dx'dy'dz': \quad . \quad . \quad (3)$$

or, writing k for the constant strength of the vortex $\iint\eta'dx'dy'$, we find

$$G=\frac{1}{2\pi}\int\frac{k}{r}dy'. \quad . \quad . \quad . \quad (4)$$

Consider now the case of a single linear vortex of strength k. Take the vortex line as the axis of y (*Fig.* 3), and let P be a point in the plane $y=0$ at which the velocities u, w are required. The motion, as we have seen, is the same in all planes perpendicular to Oy.

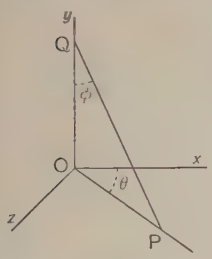

FIG. 3.

Let dy be an element of the vortex at Q, let ϕ denote the angle OQP, and θ the angle xOP, x, 0, z being the co-ordinates of P, and 0, y', 0 of Q. Put

$$QP=r=(x^2+y'^2+z^2)^{\frac{1}{2}}.$$

Then the value of G contributed by dy' at Q is

$$\frac{k}{2\pi}\cdot\frac{dy'}{r},$$

while if we denote by δu, δw the components of the velocity due to this element,

$$\delta u=-\frac{dG}{dz}=+\frac{k}{2\pi}\frac{dy'}{r^2}\frac{dr}{dz}$$

$$=+\frac{k}{2\pi}\frac{dy'}{r^2}\frac{z}{r},$$

$$\delta w=+\frac{dG}{dx}=-\frac{k}{2\pi}\frac{dy'}{r^2}\frac{x}{r}.$$

Thus, if the resultant velocity be denoted by V,

$$\delta V=\sqrt{(\delta u^2+\delta w^2)}=\frac{k}{2\pi}\frac{dy'}{r^2}\frac{(x^2+z^2)^{\frac{1}{2}}}{r}.$$

[1] See "Potential," Vol. II.

But $(x^2+z^2)^{\frac{1}{2}}=OP=h$, say,

and $$\sin\phi=\frac{h}{r}=\frac{(x^2+z^2)^{\frac{1}{2}}}{r}.$$

Therefore, writing y for y',

$$\delta V=\frac{k}{2\pi}\frac{\sin\phi}{r^2}dy, \quad . \quad . \quad . \quad (5)$$

and integrating this for the complete vortex,

$$V=\frac{k}{2\pi}\int_{-\infty}^{+\infty}\frac{\sin\phi}{r^2}dy. \quad . \quad . \quad (6)$$

Again, we have

$$\left.\begin{aligned}\delta u&=-\frac{k}{2\pi}\frac{dy}{r^2}\frac{h}{r}\frac{z}{h}=+\frac{k}{2\pi}\frac{\sin\phi}{r^2}\frac{z}{h}dy\\ \delta w&=-\frac{k}{2\pi}\frac{\sin\phi}{r^2}\frac{x}{h}dy\end{aligned}\right\}. \quad (7)$$

Thus

$$\left.\begin{aligned}\delta u&=+\delta V\sin\theta\\ \delta w&=-\delta V\cos\theta\end{aligned}\right\}, \quad . \quad . \quad (8)$$

for $z/h=\sin\theta$, $x/h=\cos\theta$.

Thus the direction of V is at right angles to the plane OPQ and in the direction from z to x.

A more complete analysis[2] shows that the expression found for V applies to an element ds of any vortex straight or curved, and the effect of an element of a curved vortex is given by

$$\delta V=\frac{k}{2\pi}\frac{\sin\phi}{r^2}ds. \quad . \quad . \quad . \quad (9)$$

In the case of a straight vortex we can readily evaluate the expression for V, for we have

$$V=\frac{k}{2\pi}\int_{-\infty}^{+\infty}\frac{\sin\phi}{r^2}dy.$$

But

$$y=h\cot\phi, \text{ and } dy=-h\operatorname{cosec}^2\phi d\phi,$$
$$r=h\operatorname{cosec}\phi,$$

therefore for an infinitely long vortex

$$V=-\frac{2k}{2\pi h}\int_0^{\frac{\pi}{2}}\sin\phi d\phi=\frac{k}{\pi h}. \quad . \quad (10)$$

If the vortex be of finite length and ϕ_1, ϕ_2 be the values of ϕ at the ends, then we have

$$V=\frac{k}{2\pi h}(\cos\phi_1-\cos\phi_2). \quad . \quad (11)$$

§ (7) VORTICES AND PRESSURE DISTRIBUTION. LIFT ON A VORTEX FILAMENT.—Consider now a stream of fluid moving from left to right with uniform velocity V, and imagine a straight vortex of strength k to be produced in the

[2] See Lamb, *Hydrodynamics*, § 145.

fluid, the axis of the vortex being horizontal and at right angles to the direction of V, while the direction of rotation is clockwise.[1] Let O, *Fig.* 4, represent the axis of the vortex, and P any point at a distance r from O. The effect of the vortex is to superpose on the velocity V a velocity v in a direction at right angles to OP, and given by the expression $k/\pi r$. The velocity is thereby increased at points above O and decreased at points below O.

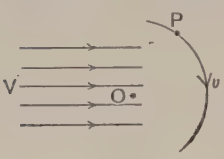

FIG. 4.

Again, if q be the resultant velocity, p the pressure, and we neglect the effect of gravity on the flow, we know that $p+\frac{1}{2}\rho q^2$ is constant along any stream line; but this quantity has the same value for all stream lines at some distance in front of the vortex, thus it is constant throughout the field.

Hence the pressure is reduced above the vortex and increased below it. There is therefore an upward force exerted on the vortex; it will experience a lift. We proceed to find an expression for this lift per unit of length of the vortex.[2]

§ (8) FORCES ON A VORTEX FILAMENT.—Imagine the vortex—treated as of infinite length—to be produced by some body surrounding its axis which is held in a horizontal position, and consider the vertical forces on the length l of a cylinder of fluid of radius r surrounding the vortex, and the change in the momentum of the fluid traversing the cylinder when the motion has become steady. Then we know that

Rate of change of upward vertical momentum
= resultant upward pressure on surface of bounding cylinder
+ resultant upward vertical pressure due to the body within the cylinder.

Consider a strip $lrd\theta$ of the cylinder, *Fig.* 5, where θ is the angle POx. The velocity of the fluid normal to this strip is V cos θ, so that the mass dm of fluid entering the strip of the cylinder per unit of time is $\rho Vlr\cos\theta d\theta$.

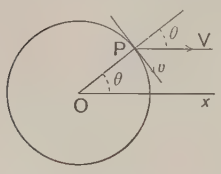

FIG. 5.

The increase in vertical velocity is $v\cos\theta$, and is positive in the downward direction.

Thus the rate of increase of the upward momentum taken over the cylinder and denoted by J is

$$-\int v\cos\theta dm.$$

Thus
$$\left.\begin{aligned} J &= -\rho lrV v\int_0^{2\pi}\cos^2\theta d\theta \\ &= -\pi\rho lrVv \end{aligned}\right\} \quad . \quad (1)$$

The pressure at any point of the surface is p, and

$$p=p_0+\tfrac{1}{2}\rho V^2-\tfrac{1}{2}\rho q^2.$$

But $$q^2=(V+v\sin\theta)^2+v^2\cos^2\theta,$$

and assuming that v^2 can be neglected compared with V^2, we have

$$q^2=V^2+2Vv\sin\theta,$$

therefore $$p=p_0-\rho Vv\sin\theta.$$

The upward vertical component of the force is found by multiplying this by $\sin\theta$, and integrating over the area. Thus the upward force on the cylinder due to the pressure

$$\left.\begin{aligned} P &= -\rho lrVv\int_0^{2\pi}\sin^2\theta d\theta \\ &= -\pi\rho lrVv \end{aligned}\right\} \quad . \quad . \quad . \quad (2)$$

Hence the resultant upward force on the fluid due to the body within the cylinder

$$\begin{aligned} &= J+P \\ &= -2\pi\rho lrVv \\ &= -2\rho Vkl, \quad . \quad . \quad . \quad (3) \end{aligned}$$

for $$v=\frac{k}{\pi r}.$$

This is the force exerted by the body on the fluid.

Hence the force on the body arising from the fluid is a lift which is given per unit of length by the expression

$$2\rho Vk.$$

We can express this force in terms of the circulation K, for as we have seen, § (5), the circulation is twice the strength of the vortex,[3] thus

$$K=2k,$$

and hence $$\text{Lift}=\rho VK.$$

§ (9) LIFT ON AN AEROFOIL.—If we imagine the body within the cylinder of fluid to be an aeroplane wing of infinite aspect ratio with its length parallel to the vortex, the expression just found gives the lift on the wing, and the theory of aeronautics developed at Göttingen by Prandtl and his colleagues assumes this to be

[1] See Prandtl, Report No. 116.

[2] This method of calculating the lift has been taken from a paper by Prandtl, translated by the National Advisory Committee of America in Report No. 116.

[3] See "Wing Surfaces, Hydrodynamical Theory of" § (1).

the case, and develops by suitable transformations a form of flow which, when combined with the appropriate circulation, leads to results in good agreement with experience.

If, for example, the obstacle take the form of a long circular cylinder and we write z for $x+iy$, then it is known[1] that the potential and stream-line functions Φ_1 and Ψ_1 are given by the equation

$$\Phi_1 + i\Psi_1 = V\left(z + \frac{a^2}{z}\right). \quad . \quad . \quad (1)$$

In this case there will be no circulation and no force on the cylinder, while the lines of flow are as in *Fig.* 6.

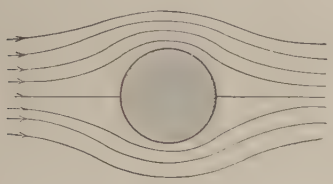

FIG. 6.

To obtain a lift we superpose on this the flow given by

$$\Phi_2 + i\Psi_2 = \frac{ik}{\pi} \log z. \quad . \quad (2)$$

This, it can easily be shown, corresponds to flow in concentric circles round the cylinder as in *Fig.* 7, with a velocity $k/\pi r$, and the resultant flow is as in *Fig.* 8. The rest points, *i.e.* the points at which two of the stream-lines meet the cylinder at right angles, are each moved downwards, and by a suitable choice of the circulation the displacement may be given any desired value.

FIG. 7.

§ (10) JOUKOWSKI'S TRANSFORMATION. — Again, if pq be the co-ordinates of a point in a

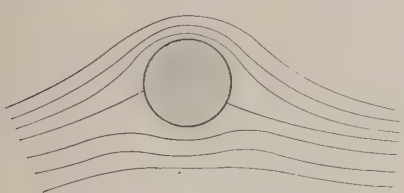

FIG. 8.

plane, the pq plane, which are connected with x and y, the co-ordinates of a point in the xy plane, by the equation

$$p + iq = \phi(x + iy),$$

[1] See "Stream-line Motion," Vol. I.

and Φ and Ψ be the potential and stream-line functions corresponding to the equation

$$\Phi + i\Psi = f(x + iy)$$

in the xy plane, Φ and Ψ are also stream-line functions for a flow in the pq plane, which can be derived from that in the xy plane. For we may write

$$x + iy = \phi^{-1}(p + iq),$$

therefore

$$\Phi + i\Psi = f(x + iy) = f\{\phi^{-1}(p + iq)\} = F(p + iq).$$

Thus Φ and Ψ are potential and stream-line functions in the pq plane. Starting from the flow with circulation round a circular cylinder, Joukowski has transformed this into the pq plane by means of the formula[2]

$$p + iq = \zeta = z + \frac{c^2}{z},$$

where $z = x + iy$, and by a suitable choice of the constants which occur has obtained, among the possible forms of flow lines, one resembling an aerofoil with a very thin trailing edge, the flow being such that one stream-line leaves the aerofoil at the edge, as shown in *Fig.* 9.

FIG. 9.

§ (11) DRAG ON A WING. *Difficulties of the Theory.*—In this case the lift on an aerofoil of the Joukowski form, arranged so as to occupy the whole breadth of a wind tunnel,[3] has been found to agree fairly with the formula. The drag on such an aerofoil is theoretically zero; in practice a slight drag was observed for angles of attack, for which the form of the wing was "good," *i.e.* was that required by the flow pattern of theory. This drag must be due to viscous action between the fluid and the aerofoil.

This indicates one obvious criticism of the theory. The equations used are those of a non-viscous fluid. In such a fluid vortex motion, involving circulation, cannot be produced by the pressures or gravitational forces acting on its particles. There is no circulation in the fluid in front of the aerofoil; in strictness there can be none, therefore, behind it.

We are forced then, on the theory, to assume that there is in the fluid a very slight amount of viscosity, which shows itself in the layer immediately surrounding the aerofoil,

[2] See "Wing Surfaces, Hydrodynamical Theory of," § (2).

[3] See also "Experiments on a Tapered Aerofoil," by A. Fage and W. L. le Page, *R. and M.*, No. 806.

where the velocity changes are very great, and is sufficient to start the circulation there, but which may, in other respects, be neglected in forming the equations of motion; this circulation, once set up, persists for a sufficient time to give rise to the state of motion in the neighbourhood of the aerofoil on which the forces acting on it depend.

§ (12) Wing of Finite Aspect Ratio.—The problem dealt with up to the present is that of an aerofoil of infinite aspect ratio, in which, therefore, the motion is two-dimensional, being the same in every plane perpendicular to the axis of the aerofoil, and the circulation is the same in each of these sections. In an actual wing of finite aspect ratio the circulation ceases at or a short distance beyond the ends of the wings, changing gradually according to some unknown law as we pass from the centre to the end of the wing. If K be the value of the circulation at a distance z from the centre of the wing $K+(dK/dz)dz$ at a distance $z+dz$, then at the point z a vortex filament of strength dK/dz is given off by the wing, and passes away as a trailing vortex in the fluid. If the value of K as a function of z be known an expression can be found for the lift on the wing, and in certain cases the integrals obtained can be evaluated. This has been done by Prandtl and his colleagues in the case when the curve representing the loading on the wing as a function of z is a quadrant of an ellipse. A further discussion of the problem will be found in another article.[1]

HYDROGEN GAS-MAKING AND THE DETERMINATION OF ITS PURITY

Hydrogen occurs in nature as a free gas, but in too small quantities for extraction. The main source of supply is water, and all commercial processes obtain it from this source. The methods employed can be divided under the following headings:

(1) From water directly.
(2) From water indirectly.
(3) Miscellaneous.

§ (1) From Water Directly. (i.) *Electrolytic.*—Distilled water, containing 10–20 per cent caustic soda or 5–10 per cent sulphuric acid, is decomposed into hydrogen and oxygen by the passage of an electric current. The main practical difficulty is to obtain efficient separation of the gases without increasing the internal resistance of the cell unduly. Various methods are employed, such as porous asbestos screens (I.O.C., Oerliken, and Burdett), iron wire gauze (Garuti), glass louvres (Churchill), separate compartments (Renard, Schoope, and Jaubert). (See "Electrolysis, Technical Applications of," VIII., Vol. II.) The theoretical voltage required per cell is 1·67. In practice this varies from 2·0 to 3·5. The volume of hydrogen produced per kw. varies from 4·5–7·0 cubic feet per hour as compared with the theoretical figure of 9·52 at 20° C. The efficiency of the cell rises as the current density per unit area of the electrode is decreased; it follows that the size of the cell increases with the efficiency. Thus the running cost is reduced at the expense of a higher initial outlay, the most profitable balance with a well-designed cell gives 6–7 cubic feet per kw.h. This method is costly unless cheap electric power is available, or unless a market can be found for the oxygen which is produced as a bye-product. The gas produced is free from injurious impurities, containing only ·3 per cent to 1·0 per cent of oxygen.

(ii.) *By the Oxidation of Iron.*—This system is largely used. Iron at 600–800° C. is oxidised by steam, thus forming hydrogen. The oxide is reduced to iron by water gas, and the process repeated. The action is

$$3Fe+4H_2O=Fe_3O_4+4H_2,$$

$$Fe_3O_4+2CO+2H_2=3Fe+2CO_2+2H_2O.$$

The iron used is calcined spathic ore. Water-gas is produced in the ordinary way, scrubbed to remove dust, tar, etc., and passed through iron oxide purifiers to remove H_2S. This is necessary to prevent fouling the ore. The reaction,

$$2CO=CO_2+C,$$

also causes fouling by depositing carbon on the ore: provision is made to admit air to burn off the carbon when necessary. The reduction phase takes twice as long as the oxidising phase: the plant is, therefore, divided into three units, so that one is on make while two are on reduce. The crude hydrogen is scrubbed and passed through lime purifiers to remove traces of CO_2 and H_2S. The final product contains ·2 to ·3 per cent CO and ·3 to ·4 per cent N_2. There are two distinct types of plant on this principle. In the Lane plant the ore is contained in cast-iron retorts which are heated externally by a producer furnace, or by burning the spent gas from the reduction phase; the heating gases do not come into contact with the ore. In the Messerschmidt plant the ore is contained in an annular space round a cylindrical heat-storage chamber, which is filled with refractory material. The spent gas from one generator is burnt in another, heating the ore and storing up heat in the central chamber ready for the reduction and oxidising phase. Some difficulty has been experienced in obtaining a satisfactory material for the liner, which separates

[1] See "Wing Surfaces, Hydrodynamical Theory of," § (3).

the central chamber from the annular space containing the ore.

Bergius heats finely-divided iron and water in a liquid state beyond its boiling-point in a closed vessel to about 300° C. He claims complete oxidation of all the iron present, with the evolution of hydrogen, which is given off at 150 atmospheres and can be charged direct into bottles without compressors.

§ (2) From Water Indirectly. (i.) *Catalytic Process.*—Water-gas is made in the usual way and purified from H_2S. It is then mixed with steam and passed through a chamber at 400–600° C. containing a catalyst, such as iron, nickel, cobalt, chromium, etc. The following action takes place:

$$CO + H_2O = H_2 + CO_2.$$

The reaction is exothermic, and the heat given off is sufficient to maintain the working temperature. The resultant hydrogen contains 1-3 per cent CO, 1-4 per cent N_2, and about 30 per cent CO_2.

The latter is removed by washing with water under pressure, the final trace by caustic-soda solution. The hydrogen obtained is theoretically equal to the volume of the water-gas used; in practice about 80 per cent is obtained. The percentage of nitrogen in the final product is slightly higher than that in the original water-gas, and renders this method unsuitable for aeronautical work.

(ii.) *Linde-Frank-Caro.*—Water-gas, purified from H_2S, is compressed to 20 atms. and washed with water under pressure to remove the CO_2, the last trace being absorbed by caustic soda or lime. It is then cooled by an ammonia refrigerating plant to −35° C. to dry it. It then passes, still under pressure, through a condenser cooled by liquid CO; this condenses most of the CO and N_2. The gases and liquid pass through a separator and the gas is again cooled to −205° C. by liquid nitrogen boiling under reduced pressure. The resultant gas contains 1·5–2·5 per cent CO and ·5 to 1·5 per cent N_2. The CO is sufficient for producing the necessary power for the compressors, pumps, etc.

§ (3) Miscellaneous. (i.) *Silicol.*—This process was largely used for war purposes. The silicol used is made by heating silica in an electric furnace with coke to about 3000° C., the reaction being

$$SiO_2 + 2C = Si + 2CO.$$

The resultant product is run off into a mould, cooled, and ground to pass a 30-mesh sieve. It contains about 90 per cent silicon, 4 to 5 per cent each of iron and aluminium, with traces of calcium, arsenic, and phosphorus. The silicol is fed slowly into the generating chamber, which contains a hot 35–40 per cent solution of caustic soda. The reaction is

$$Si + 2NaOH + H_2O = Na_2SiO_3 + 2H_2.$$

This reaction is exothermic, and no additional heat is required. Large quantities of gas can be produced at short notice by this method, and the plant is simple to construct. The high cost of the materials used makes it unsuitable for commercial use. The gas contains traces of arsene and phosphine.

(ii.) *Oil Cracking.*—Oil is sprayed into a furnace or retort at a temperature of 1500 to 3000° C., the hydro-carbons are split up, the carbon being deposited as lamp-black, which is a valuable by-product. The resultant gas contains 2 to 3 per cent of CO and 2 to 3 per cent hydro-carbons, and 1 to 2 per cent nitrogen. Difficulty is experienced in finding material for the retorts which will stand the high temperatures. Coal-gas can be cracked in a similar manner.

(iii.) *Decomposition of Acetylene.*—Acetylene is compressed to 5 atmospheres and decomposed by an electric spark. The carbon is deposited as lamp-black. Compressing acetylene was found to be dangerous. A bad explosion occurred in using this process at Friedrichshafen in 1910.

(iv.) *Hydrolith.*—Calcium hydride is made by passing electrolytic hydrogen into metallic calcium heated to a high temperature. This gives off hydrogen when mixed with water,

$$CaH_2 + 2H_2O = Ca(OH)_2 + 2H_2.$$

This process is only used for military purposes, owing to high cost.

§ (4) The Determination of Purity of this Gas.—The only accurate method is by chemical analysis. The gas is burnt or exploded with air or oxygen and the quantity of hydrogen calculated from the volumetric contraction. The usual apparatus employed in gasworks is unsatisfactory, owing to the high percentage of hydrogen compared with the other constituents. Hempel's apparatus usually underestimates the hydrogen content by 1·0 to 1·5 per cent; Bone and Wheeler's apparatus gives reliable results, but is not handy to use. A specially designed apparatus in which 100 c.c. of the gas can be burnt with a known volume of oxygen gives reliable results and is easier to use. Another method is to pass 500 c.c. of the gas through a tube containing finely divided copper oxide heated to a red heat. The copper oxide is reduced and the hydrogen is converted into water.

Several instruments are made on the principle of Graham's law for the diffusion[1] of gases. The times are taken for equal volumes of the gas and air to escape through

[1] See "Diffusion through Membranes," § (2).

a small hole. The densities are inversely proportional to the squares of the times. The Wright meter consists of an inverted bell containing the gas or air, suspended over a vessel containing glycerine and water. The bell in falling moves a pointer over a scale, and the times for gas and air are taken between two marks. In the Schilling meter the gas is contained in a vertical glass tube, and the time the water takes to pass two marks as it rises is taken. These instruments only give an accuracy of ± 1 per cent.

The Shakespeare[1] Purity Meter depends upon the heat conductivity of the gas varying with the percentage of air mixed with it. A constant current from a 2-volt cell is passed through two coils of wire; one coil is in a vessel containing air, the other in a vessel through which the gas to be tested is pumped. The coil in the gas cools more rapidly than the one in air, altering its resistance, which is measured on a Wheatstone bridge. The cooling effect of the gas varies with its purity, and the galvanometer is graduated to read in percentages of hydrogen. W. P. R.

[1] See "Diffusion through Membranes," § (8).

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— I —

INFLAMMABILITY OF DOPED FABRIC. See "Aeroplane Wings, The Doping of," § (7).

INTERFERENCE ERRORS as applied to instruments used in aircraft. See "Aircraft, Instruments used in," § (6) (ii.).

INTERFEROMETER, for gases: an instrument for indicating the concentration of a gas by the refractive index. See "Diffusion through Membranes," § (7).

— J —

JOY STICK. See "Aeroplane, Component Parts of"; also "Aircraft, Stability of," § (2) (v.).

— K —

KATHAROMETER: an instrument for indicating the concentration of a gas by the variations in its thermal conductivity. See "Diffusion through Membranes," § (8).

— L —

LAG OR CREEP ERROR AS APPLIED TO ALTIMETERS. See "Aircraft, Instruments used in," § (3) (ii.).

LATERAL CONTROL OF AEROPLANES. See "Aerodynamic Research, Full Scale," § (23).

LEADING EDGE. See "Aeroplane, Component Parts of."

LIFT: the component of the force acting on an aircraft arising from the resistance of the air, which acts in a direction at right angles to that of the relative motion.

Determination of, on full-scale aeroplanes. See "Aerodynamic Research, Full Scale," §§ (10) and (12).

LIFT AND DRAG, CURVES OF. See "Flight, Principles of."

LIFT AND PITCHING MOMENT. See "Model Experiments in Aeronautics," § (7) (ii.), (iv.).

LIFT, SPEED, AND ANGLE OF ATTACK, CURVES OF. See "Flight, Principles of."

LINEN AS USED FOR AIRCRAFT. See "Aeroplane Wings, Fabrics for," §§ (1) and (12).

LINSEED OIL as a proofing for balloon fabrics. See "Diffusion through Membranes," § (15) (ii.).

LOADS, calculation of, on aeroplane wings. See "Aeroplane Structures, Experiments," § (4).

LONGERONS. See "Aeroplane, Component Parts of."

LONGITUDINAL CONTROL OF AEROPLANES: effect of position of centre of pressure on the wings, tail plane characteristics, and slip stream of the airscrew. See "Aerodynamic Research, Full Scale," § (22).

— M —

MEMBRANES, STRETCHED, rates of passage of various gases through. See "Diffusion through Membranes," § (3).

MODEL EXPERIMENTS IN AERONAUTICS, THEIR THEORY AND METHODS

I. INTRODUCTORY REMARKS

THE use of model experiments as a guide to full-scale design was well established before the days of aeronautics, being in extensive use in connection with ship construction, to mention a specific case. It was soon realised that the only practicable way to obtain detailed information concerning the behaviour of the wings and other parts of an aeroplane was by tests upon models in a current of air. In any type of model tests it is necessary to determine the law connecting results obtained upon the model and the corresponding full-scale figures, and this can be done by making use of the fact that the dimensions in mass, length, and time must be the same on both sides of any physical equation. For example, in the case of tests on ship models, the part of the resistance due to wave-making can be shown to be proportional to

$$\rho v^2 l^2 f\left(\frac{v^2}{lg}\right),$$

where ρ is the density of the fluid (water in this case), l is a length (*e.g.* the length of the ship) defining the geometric scale of the system, v is the forward speed, and g is the acceleration due to gravity.

The form of the function $f(v^2/lg)$ cannot be deduced from general considerations, and would only become known if the complete hydrodynamic problem of the motion of a body in a fluid could be solved. But it is evident that if the model can be tested at a value of v^2/lg, which is the same as that for the actual ship, a direct prediction of the ship's resistance can be made from the model test without a knowledge of the form of the above function, since $f(v^2/lg)$ will be the same for both model and ship. The above function is merely a mathematical statement of Froude's law of comparison, *i.e.* that the speeds of model and ship must be proportional to the square roots of their lengths in order that the comparison may be true.

In the case of model tests in a wind tunnel the above law does not hold, since there is no free surface of the fluid, and therefore no wave motion. Instead of g, the viscosity of the fluid is the determining factor, and it is convenient to use the quantity known as the kinematic viscosity ν, *i.e.* the ordinary viscosity coefficient μ divided by the density ρ. An application of the theory of dimensions[1] shows that the force F acting on any body in a moving fluid, there being no free surface waves, can be expressed by a relation of the form

$$\mathrm{F} = \rho v^2 l^2 f\left(\frac{vl}{\nu}\right),$$

where the symbols have the same meaning as in the case given before, with the addition of ν, the kinematic viscosity.

It is immediately obvious that to obtain dynamical similarity in model tests of this nature, it is necessary to work at the same value of vl/ν for the model and full-scale aircraft, and if the tests are made in a wind tunnel, so that ν is the same in both cases, then vl must be constant. This involves testing the model at a speed *greater* than that of the actual aircraft in the inverse proportion of the scales of model and machine, a proceeding which is manifestly impracticable, since such high speeds are not obtainable, and even if they were, the theory would break down owing to the effect of compressibility becoming important as the speed of sound in air was approached. There remains nothing to be done but to determine the variation of $f(vl/\nu)$ over as large a range as possible, and to rely on full-scale tests for a confirmation of the model predictions. Fortunately the value of the above function becomes sensibly constant at the higher wind-tunnel speeds for most types of model, and full-scale tests indicate that there is little change of its value in the unexplored interval between model and full scale: that is to say, the force generally varies very nearly as the square of the wind speed and the square of the linear dimensions. The use of model experiments in aeronautical work is therefore less direct than in the case of ship design, and considerable judgement is necessary in applying the results to the full scale. The vast accumulation of data during the last ten years has, however, placed the use of model tests on a firm basis, although there are still cases (*e.g.* airship resistance) where, from lack of full-scale data, the interpretation of the model results is still somewhat indefinite.

Most of the model data have been obtained in a wind tunnel, which is essentially an apparatus for producing a uniform steady current of air in which the model is held

[1] See "Dynamical Similarity," Vol. I

whilst observations upon it are taken. Usually the model is mounted on some special form of balance for measurement of forces and moments, and is stationary. In experiments on stability, however, it may be mounted so that it is free to oscillate about an axis, or about two axes at right angles. Before describing the wind tunnel and its use, some mention should be made of two pieces of apparatus—the whirling arm and the water channel—both of which were extensively used in the early days of aeronautical model experiments at the N.P.L. (The apparatus and methods described later are for the most part those in use at the N.P.L., where the greater part of the pioneer work in experimental aeronautics was done.)

II. Experimental Apparatus

§ (1) The Whirling Arm.—This apparatus is now no longer in use, but is of fundamental importance, since by its means the standard pitot and static-pressure tube was calibrated, thus providing the standard of wind speed which is a necessity in the use of the wind-tunnel. The whirling arm at the N.P.L. consists of a vertical shaft carrying two diametrically opposite arms built up of light steel angle stiffened by means of wiring. The arms are each about 30 ft. in length, the apparatus standing in a shed 80 ft. square. The shaft carrying the arms is rotated by a 14-h.p. motor, and speeds up to about 50 ft. per second at the end of the arm can be obtained. The whirling arm was extensively used for testing air-screws in the early days of the aeronautical work at the N.P.L.,[1] but this work is now carried out in a 7-ft. wind-tunnel. The whirling arm is the only convenient means by which an accurately known velocity relative to the air can be produced, and this fact rendered it an invaluable piece of apparatus for the absolute calibration of a pressure anemometer which could afterwards be used as a standard instrument for the calibration of wind speed in the wind-tunnels. The N.P.L. pitot and static-pressure tube was designed, and calibrated on the whirling arm,[2] and it was shown that a tube can be made which will give a pressure difference of $\frac{1}{2}\rho v^2$ within $\frac{1}{5}$ per cent, and which can be duplicated, with reasonable care in manufacture, without fear of errors exceeding the above figure.

§ (2) The Water Channel for Experiments on Fluid Flow.—It was soon found desirable to visualise the flow past an obstacle in a fluid, so that qualitative ideas of the nature of flow could be readily obtained. For this purpose a small water-channel was constructed, as is illustrated in *Fig.* 1. The channel itself is 8 ft. long, 3 in. wide, and 6 in.

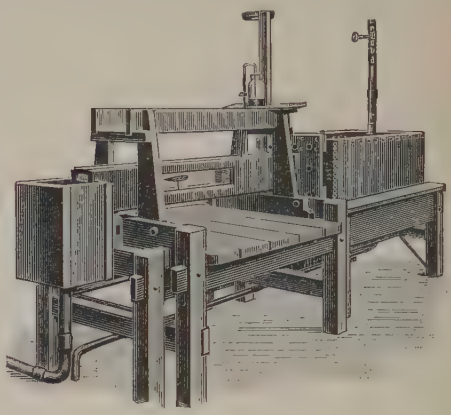


Fig. 1.

deep, one end entering a large tank, and the other being provided with a V-notch for regulating the rate of flow of the water. Water is admitted to the tank from the ordinary water mains, and speeds up to about 2 in. per second are obtainable in the channel. It is, however, impossible to work satisfactorily at speeds above the critical speed for the channel, which is just over 1 in. per second. Small models are placed in the channel, which is provided with glass sides over a length of about 2 ft., and the flow is rendered visible by the injection of coloured fluid, red ink being suitable if the flow is to be visually observed, while a weak solution of Nestlé's milk was found to be excellent for photographic purposes. The channel in the neighbourhood of the model is illuminated by two arc lamps provided with cylindrical lenses which concentrate the light in a narrow horizontal beam. When it is desired to obtain a record of the velocity and direction of flow at every point of the fluid, a large number of small oil-drops are injected into the channel by means of a small water-jet impinging on the lower end of a fine vertical tube supplied with oil. The drops are introduced at a considerable distance from the model, so that the disturbance caused by the injection has died away before the oil-drops reach the model. After considerable trouble a mixture was found which had the same density as water, and which also gave drops of such a refractive index that light entering them horizontally was for the most part emitted vertically. Each drop, viewed from above, appears as a brilliant point of light, and by giving a short-time exposure a photograph can be obtained in which each

[1] *Report of Advisory Committee for Aeronautics*, 1909–10, i. 15, 16; also *ibid.*, 1910–11, ii. 52.
[2] *Ibid.*, 1912–13, iv. p. 35.

drop traces a short line on the plate, whose direction shows the direction of flow at the point and whose length gives a measure of the velocity at that point. A photograph is reproduced (*Fig.* 2) showing the fluid motion behind a cylinder, in which both condensed milk and oil-drops were used. It is immediately apparent that while the milk shows up the position and size of the eddies clearly, it may give very misleading ideas of the direction of flow. Thus at A, in the photograph, one might imagine that the fluid was moving in the direction indicated by the filament of milk in that neighbourhood, but the oil-drops show that the flow is almost perpendicular to this direction. In general it can be stated that a cloud of smoke or coloured fluid will show the presence of eddies, but it is necessary to introduce small particles whose motion can be *individually* traced, if a knowledge of the direction of flow at various points in the fluid is to be obtained.

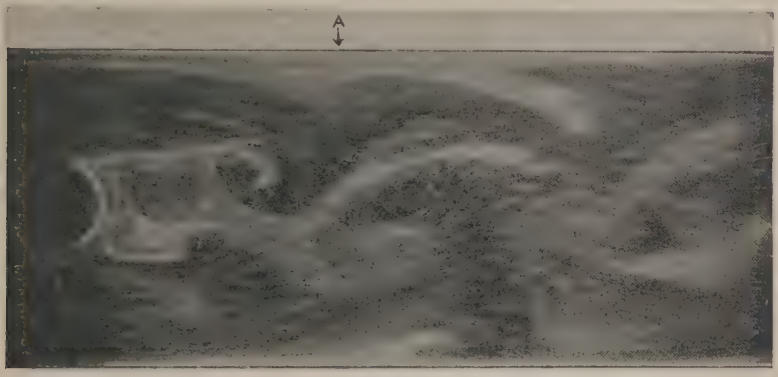


FIG. 2.

By means of the water channel, much information has been obtained as to the general nature of flow behind aerofoils. It has been shown that the "critical angle" at which the lift reaches a maximum and the drag increases very rapidly corresponds with the angle at which eddying motion commences. By the use of a cinematograph camera it has been established that the eddying flow behind a cylinder is truly periodic, values of velocity and direction obtained from different photographs of the same phase being in remarkably good agreement.

§ (3) THE WIND TUNNEL. *General Description.*—By far the most important piece of apparatus in aeronautical model experiments is the wind tunnel, which consists in essence of a tube in which a steady current of air can be maintained, and in which arrangements are made for measuring the forces and moments produced by the action of this air current upon models.

(i.) *The N.P.L. Tunnels.*—It is interesting to note that the present successful type of wind tunnel in use at the N.P.L., which is described in detail in § (4) below, was itself the result of model experiments. It was realised that the two main desiderata in wind-tunnel design are the provision of an air stream of uniform velocity over the greater part of the cross-section of the tunnel, and in which the variations with time from the mean value of the velocity are small. To obtain an even-velocity distribution it is necessary to work near the intake of the tunnel, the distribution becoming in consequence of friction more and more nearly parabolic as the distance from the inlet increases. For a steady flow, it is necessary to use a fan of low pitch to produce the current, a high-pitch fan or any type of centrifugal blower giving a very unsteady wind. The design of tunnel which would best satisfy these requirements was determined by experiments upon a small model tunnel 6 in. square in cross-section, and placed inside a model room made up with cardboard on wood frames. The distribution of velocity across various sections was explored with a Pitot tube, and the steadiness of the wind was measured by attaching a photographic recording gauge to the Pitot tube. By these means it was possible to determine the effect of modifications to the design on the steadiness and distribution of the wind produced, and also to determine the minimum size of room in which a tunnel could be satisfactorily used. As a result of these experiments the 4 ft. No. 1 tunnel was constructed, and proved perfectly satisfactory and in accordance with what would be anticipated from the experiments on the 6 in. model. Measurements showed that the velocity over a 3 ft. square of

the cross-section was everywhere within ± 1 per cent of the mean value, so that the wall disturbance extended less than 6 in. from the wall. The steadiness records showed few fluctuations exceeding ± 2 per cent of the mean velocity, with considerable intervals in which the fluctuations were less than ± 1 per cent. Since the date of this 4 ft. tunnel (1911–12), a 3 ft. tunnel, another 4 ft., and three 7 ft. tunnels have been built on substantially the same lines, and in every case similar results as to distribution and steadiness have been obtained. In the latest 7 ft. tunnel the variation of velocity over the centre 5 ft. square is within $\pm \frac{1}{2}$ per cent of the mean speed.

In addition to the wind tunnels just enumerated, a larger tunnel of special design has been installed. This tunnel has a rectangular cross-section 14 ft. wide and 7 ft. high, so that it admits the doubling of the scale of models such as aerofoils and complete aeroplanes, in which the wing span is the limiting factor in a square-section tunnel. The rectangular tunnel divides into two separate expansion cones at the back honeycomb, and an air-screw works in each cone. It was found, as a result of tests on a model tunnel, that in order to secure steadiness in running it was necessary to gear the two air-screws together. If this was not done, a violent oscillation was set up, the wind fluctuating between the two air-screws. In the actual tunnel mechanical gearing was unsuitable and the two motors have been synchronised electrically. A novel feature of the installation is the provision of a honeycomb wall built right across the room at the end of the straight section of the tunnel. This wall adds greatly to the steadiness of the tunnel and allows the usual "distributor" behind the air-screws to be much shortened. The "Duplex" tunnel, as it has been named, has proved a complete success. The flow is steadier than that in the 7 ft. No. 3, the distribution of velocity is very uniform, and the wind direction at the working section is nowhere more than $\frac{1}{10}$ degree from the centre line of the tunnel. This tunnel will render possible research on the effect of the air-screw slip-stream of an aeroplane, since it admits a model large enough to carry a 1 h.p. electric motor. Measurements of forces and stability derivatives will be made with an air-screw in place and running on the model aeroplane, thus reproducing completely the conditions of flight under power on the actual aircraft.

The original 4 ft. tunnel gave wind speeds up to 50 ft./sec. The later tunnels gradually increased the speed range, and at the present time 100 ft./sec. is attainable in the 7 ft. No. 3 and 120 ft./sec. in the duplex tunnel.

The following figures give details of these tunnels:

Tunnel.	Air-screw Diameter.	R.P.M.	H.P.	Speed. Feet per Sec.
4 ft. Nos. 1 & 2 .	5′ 6″	1800	20	75
7 ft. No. 1 . .	11′ 6″	1200	60	65
7 ft. No. 2 . .	11′ 6″	1250	120	80
7 ft. No. 3 . .	11′ 6″	1350	200	100
Duplex . . .	11′ 6″ (2 air-screws)	1400	400	120

(ii.) *R.A.E. Tunnel.*—At the Royal Aircraft Establishment a 7 ft. tunnel has been built which combines to some extent the N.P.L. and Continental types. The working section of this tunnel is square in section, and of similar dimensions to that of the N.P.L. 7 ft. tunnels, but the short expansion cone is replaced by a long diverging cone similar to that of the Continental tunnels. A honeycomb wall across the room is used in place of the usual diffuser, as in the duplex tunnel. A wind speed of about 130 ft./sec. is obtained with an expenditure of 200 h.p.

(iii.) *Continental Tunnels, France.*—On the Continent, wind-tunnel design has taken very different lines. The basic difference consists in the employment of a long diverging cone at the exit of the working part of the tunnel, in which the velocity of the air falls gradually as the fan or blower is approached, and the air is finally discharged into the room at a much lower speed than in the N.P.L. type. This results in a large saving of kinetic energy wasted in the issuing stream, and a considerably higher wind speed in the tunnel can be obtained for a given expenditure of power. In many tunnels of this type the inlet and outlet cones are attached to a central chamber across which the air current travels without being confined by a solid wall. This chamber is made air-tight, as the pressure within it is roughly $\frac{1}{2}\rho v^2$ below the atmospheric pressure. While there are at present no direct comparative data, it is known that the distribution and steadiness in the above type of tunnel are inferior to the corresponding conditions in the N.P.L. type, and the extra velocity obtainable is dearly purchased at the expense of accuracy of measurement of the forces and moments produced by the action of the wind upon models.

(iv.) *Continental Tunnels, Germany.*—Another Continental type is the so-called "race-course" tunnel, in which the air makes a complete circuit and is never discharged into the room. The greatest difficulty experienced in this type of tunnel is in obtaining

a uniform distribution of speed across the working section, which must of necessity be within distance of a few tunnel diameters from a right-angle bend if the dimensions of the whole apparatus are at all reasonable. Devices consisting of curved blades are employed at the bends, and these blades are individually adjusted by bending them until the desired distribution at the working section is attained. A further disadvantage of this type lies in the fact that the air in the tunnel has little chance of losing the heat imparted to it from the propeller, and the temperature in the tunnel soon rises to an undesirably high value at the higher wind speeds.

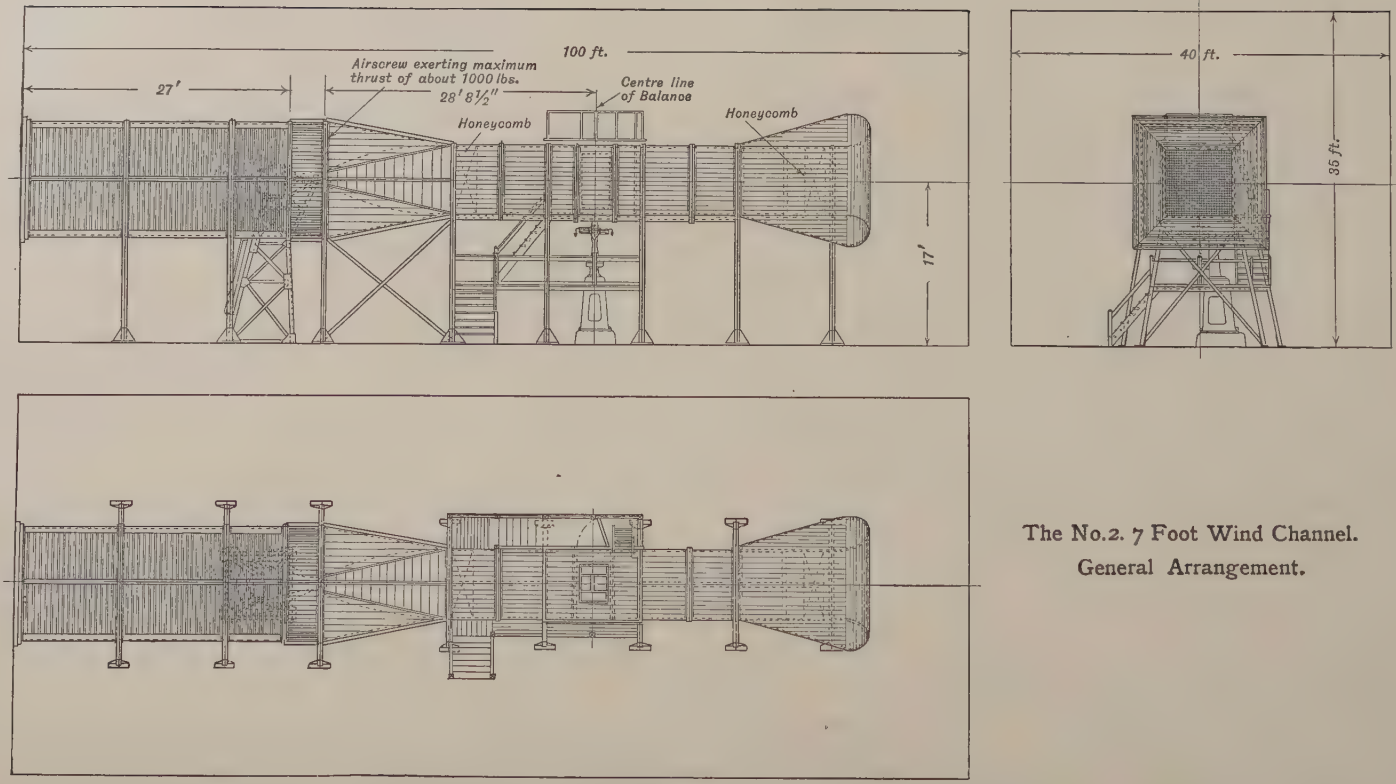
Recent reports on the new tunnel at the Göttingen Laboratory indicate that many of the difficulties of the "racecourse" type have been overcome. A system of narrow blades at the right-angle bends has been devised which produces a regular stream at the working section without the individual adjustment of the blades which was previously found necessary. The steadiness and distribution of wind speed in the Göttingen tunnel appear to be very similar to the conditions obtaining in the N.P.L. type.

The general trend of Continental wind-tunnel design has been to obtain increased speeds in a tunnel about the size of the N.P.L. 7 ft. tunnels. It is more advantageous in many ways to increase the size of the tunnel rather than the speed. At 80 ft. per second in a 7 ft. tunnel the forces due to the wind are already so large that the question of distortion of the model and its supports is becoming serious. If the working value of vl/ν is doubled by doubling the speed, the forces are increased fourfold on a model of the same size, and the distortions also multiplied by four. If, however, the scale can be doubled instead of the speed, the same value of vl/ν is realised, but the double-size model is strong enough to prevent serious distortion. Moreover, the larger model enables details to be represented with greater accuracy. The N.P.L. Duplex Tunnel was built with this reasoning in view, in preference to a high-speed tunnel with a 7 ft. square section.

§ (4) N.P.L. Type Wind Tunnel. *Details.*—It is now proposed to give a more detailed description of the N.P.L. type of tunnel, and for this purpose the 7 ft. No. 2 tunnel will be considered. A general arrangement drawing of this tunnel is given in *Fig.* 3. The tunnel is housed in a room 100 ft. long, 40 ft. wide, and 35 ft. high, and which is kept clear of any large obstructions which might influence the regularity of the air flow. The tunnel is built of wood and supported on steel framing resting on concrete foundations. The 7 ft. square section extends from the intake to a distance of 45 ft., after which it is expanded to a circular section in which the air-screw works. The length of this expanding portion is 13 ft.

The air-screw is very similar in general appearance and blade shape to an ordinary four-bladed aeroplane air-screw, but blade angles are necessarily different owing to the different conditions of running. The air-screw was designed on the aerofoil strip theory, and when tested, was found to give the desired wind speed within 1 or 2 ft. per second. The motor driving the air-screw is of 120 h.p., 400 volts D.C., the line voltage being kept constant within about $\pm\frac{1}{2}$ per cent by means of a Tirrill regulator.

Behind the air-screw is the diffuser or distributor, whose function is to cause the air to return to the room at low velocity over a large outlet area. The diffuser is 27 ft. long and 12 ft. square in section. It is formed of a large number of battens secured to suitable framing and having spaces between them. These slots are numerous and wide near the air-screw end, and become progressively fewer and narrower as the far end is approached. The dimensions and distribution of the slots were obtained in the first instance from trials on the six-inch model tunnel previously mentioned, and slight improvements were effected in the later tunnels by measuring the outflow velocity through the diffuser slots of the earlier tunnels, and adjusting the width and distribution so as to render the outflow velocity as nearly constant as possible over the whole length of the diffuser. The intake end of the tunnel is fitted with a curved mouthpiece to prevent the formation of eddies which would occur at any sharp edge. The curve of the intake is faired into the straight part of the tunnel so that the radius of curvature increases continuously. There are two "honeycombs" in the tunnel, one near the intake and the other immediately in front of the expanding section. These honeycombs were found to be essential if rotary motion of the air stream about the longitudinal axis of the tunnel was to be prevented, and they also increase the steadiness of flow at the working section. The front honeycomb is the more important of the two in these respects. The honeycombs are built up of tinned plate, and have cells $3\frac{1}{2}$ in. square, the length in the direction of the air flow being 2 ft. They are made in two pieces, for convenience in erection; the joint between the two pieces being horizontal and 1 ft. from the tunnel roof, so that the double thickness of metal at the joint does not lie immediately in front of the model. The working section of the tunnel is 29 ft. from the intake, and the tunnel at this point is provided with trap doors in roof and floor, and a glazed door at one side for access. The motor and air-screw



The No.2. 7 Foot Wind Channel.
General Arrangement.

FIG. 3.

are supported on a separate steel framework which nowhere touches the woodwork of the tunnel. This ensures that as little vibration as possible is communicated to the tunnel structure, a consideration of much importance, since balances of various kinds are often mounted on the tunnel itself. The wind speed in the tunnel may be measured by means of the Pitot and static pressure tube [1] used in conjunction with a sensitive pressure gauge such as the Chattock Tilting Manometer,[2] but, in practice, it is inconvenient to have a Pitot and static tube always in position in the channel. For the N.P.L. type of channel a very simple and convenient method of measuring the wind speed is afforded by the facts that the pressure inside the channel when the wind is on is less than the pressure in the building containing the channel, and that this difference in pressure between inside and outside of the channel is proportional to ρv^2, as also is the difference of pressure between the two sides of a Pitot and static pressure tube placed in the tunnel. A hole in the side of the channel is, therefore, connected to one side of a pressure gauge, the other side of which is open to the room. Readings taken on this gauge at the same time as readings taken on a gauge connected to a standard Pitot and static pressure tube set up in the channel supply the connecting link required to convert the former readings to air speed, and when this calibration has been done, it is no longer necessary to have a Pitot and static tube in the channel for the purpose of measurement of wind speed—unless, of course, it is required to measure the distribution of velocity around a model in position. The figures of the calibration are worked out for a standard density corresponding to a standard barometric height of 760 mm. and a temperature of 15° C. The one set of figures is always adhered to, even when the density is not standard, in which case the wind speed is not truly the nominal speed. But adherence to the one set of calibration figures, regardless of barometric height and temperature, has an advantage in that it means working with a constant value of the quantity ρV^2, with which quantity vary both pressures and forces on models placed in the channel.

The hole in the side of the tunnel is placed well up-stream of the working section, so that the suction in it is unaffected by the introduction of the models. Convenient electrical controls for regulation of the speed of the motor are placed on the platform under the tunnel, and it is possible to obtain any wind speed between 20 and 80 ft. per second, fine regulation being secured by a field resistance which can be placed in any convenient position on the platform.

[1] *Report of Advisory Committee for Aeronautics*, 1912–13, iv.; see also "Friction," § (11), Vol. I. 35.

[2] *Report of Advisory Committee for Aeronautics*, 1915–16, vii.; see also "Pressure, Measurement of," § (27), Vol. I. 37.

III. Experimental Methods

Having described the principal piece of apparatus which is used for model experiments in aeronautics, namely, the wind tunnel, it is now proposed briefly to outline the various methods which are adopted in the different types of experiments for which a wind tunnel is suited. These types may broadly be classed as follows:

(*a*) Measurement of wind velocity (speed and direction) around models.

(*b*) Measurement of the distribution of pressure over models.

(*c*) Measurement of forces and moments on models and parts.

(*d*) Stability experiments; measurement of rotary derivatives, auto-rotation.

(*e*) Tests on air-screws.

§ (5) Measurement of Wind Velocity (Speed and Direction) around Models.—When measuring the air speed near a model it is sometimes necessary to employ a combined Pitot and static tube much smaller than the standard, or even to employ separate Pitot and static tubes. Two reasons may make it advisable to adopt the latter course: it sometimes happens that the static pressure near a model changes rapidly along the direction of flow, so that if a combined Pitot and static tube is used there is an error due to difference in static pressures at the mouth of the Pitot tube and at the static pressure holes. Again, with models which are small and/or with measurements which are required to be taken very near to the model, it may not be possible to make the combined Pitot and static tube so small that it will not produce appreciable interference with the air flow round the model, with consequent error in results. One trouble which is often encountered in the use of either separate or combined Pitot and static pressure tubes is that the direction of the wind is not known with sufficient accuracy for setting Pitot and static tubes along it.

The velocity and direction meter (described below) could be used in such a case, but each observation of velocity is somewhat laborious with this instrument. If it is known roughly what the wind direction is, and if measurement of speed is all that is desired, the "sphere suction meter" or "cylinder suction meter" may be used. The principle of these instruments is that the suction at the back of a sphere or cylinder placed with its axis across the wind current is a function of both the pressure and velocity of the wind, and is the same over a considerable range of angle of presentation to the wind. In the case of

the sphere suction meter, calibration of the instrument is scarcely affected by an angular deviation between the axis and the wind direction of about $\pm 10°$, and of about $\pm 20°$ in the case of the cylinder suction meter.

(i.) *The Velocity and Direction Meter.*—This instrument, commonly called a "yawmeter," is the only satisfactory device so far devised for mapping the flow round models in the wind tunnel. It depends for its action on the fact that when a Pitot tube is inclined at an angle between 45° and 65° to the wind direction, the change of pressure in the tube for a small change of angle is great. If two tubes inclined at such an angle are used, the difference of pressure between them will be zero when the wind direction bisects the angle between them. Any deviation of wind direction will increase the pressure in one tube and decrease it in the other, and it is found that a change of even $\frac{1}{10}°$ at wind-tunnel speeds produces a difference of pressure easily observable with a tilting manometer. It is obvious that if such a pair of tubes is mounted so that it can be rotated about an axis perpendicular to the plane of the tubes, it is easy to determine the wind direction at any point by rotating the tubes until the manometer indicates zero reading. This, of course, only applies to two-dimensional flow. The velocity and direction meter was designed to apply the above principle to three-dimensional flow. The instrument is depicted in *Fig.* 4. It consists of two pairs of tubes, one pair in a horizontal and the other in a vertical plane. The tubes are bent inward rather than outward at the open end, so that the direction of flow is measured practically at a point in space. A small hollow cone is fitted behind, where the four tubes meet, and a fifth tube enters this cone and is open to the interior of the conical space. The instrument is usually mounted on the main balance, the model being moved so that the direction meter occupies the position relative to the model at which observations are required. The top part of the balance is rotated until the pressure difference between the horizontal pair of tubes is zero, thus locating the vertical plane containing the wind direction. The pressure difference between the vertical pair of tubes is then observed, and also the difference between the pressure at either horizontal tube and the suction in the hollow cone. From these two readings the direction in a vertical plane and the velocity are found from a calibration chart, which is previously constructed by testing the "yawmeter" at various angles and wind speeds in the free tunnel. In a later instrument it is possible to adjust the angle of the instrument in both horizontal and vertical planes so that the pressures in all four tubes are equal. This results in a great simplification, since both angles are obtained directly by a null method, and only a single calibration is necessary to give the wind speed. The tubes are made of hypodermic tubing of about 1 millimetre diameter, so that the instrument is very small, compared with the model, and records sensibly the velocity and direction at a point in space.

Fig. 4.

Although the accuracy is excellent, the "yawmeter" cannot be considered a completely satisfactory instrument as regards speed of observation of readings, especially in cases where it requires to be made of very small tubing, thus causing the pressure gauge used in conjunction with the instrument to be very heavily damped. There is therefore a need for an instrument of small size which will determine air speed and direction more rapidly than has hitherto been possible.

§ (6) Measurement of Pressure Distribution.—The general method adopted in all measurements of pressure distribution is the same. The pressure at any point on the surface of a model is found by making a very small hole in the model at that point and connecting the hole through tubing to one side of a pressure gauge in such a way that the tubing does not interfere appreciably with the flow of air in the vicinity of the hole. The other side of the gauge is generally connected to the hole in the side of the channel. The pressures actually required in these measurements are the pressures above or below the pressure which obtains in the region of the wind channel occupied by the model, when the model is removed, and a small correction has therefore to be made for the difference between the static pressure as found from the hole in the side and the static pressure in the empty channel at the region where the model is placed. The type of pressure gauge which is used depends upon the magnitude of the pressures to be measured and on the accuracy desired. For most purposes, however, a Chattock tilting manometer is satisfactory.

Models made for the purpose of "pressure plotting" may be either in wood or metal according to the class of model. In the case of models made of wood—airship models, for instance—a good plan is to cut a groove along the line on which it is desired to observe pressures and place in it a piece of metal tubing so as to be flush at the surface, the spaces at the sides being filled with wax. Holes are then bored at intervals along the tube. A model such as an aerofoil, tailplane, or rudder would

be made of metal, either brass or light alloy, but preferably brass, and tubes would be let in and made up flush with the surface by means of solder. For an aerofoil over which distribution of pressure was desired for the whole surface a series of parallel tubes would be let into the under surface parallel with the direction of the span, and holes bored into the tubes from upper and lower surfaces at given sections along the span. All the holes would then be stopped up and the model tested for leaks with a special U-tube, after which the holes at one section of one surface of the aerofoil would be cleared and observations of pressure taken for those holes at all the desired angles of incidence. After closing up these holes it is a wise precaution to test for leaks again before uncovering another set of holes.

Plasticine has been used for stopping up the holes, but there is a danger with its use of the tubes becoming choked up, and a better method of stopping is to use discs of thin paper, about a quarter of an inch in diameter, stuck over the holes with seccotine diluted with about an equal quantity of water, the discs afterwards being given a coating of this mixture.

It is important that the holes should be free from any projecting burr, as this is found to have a considerable effect on the pressure at a hole. Holes are generally made about 0·02 in. in diameter.

One of the most difficult and important pieces of work on pressure distribution has been carried out by Fage and Howard, who have been successful in finding the distribution of pressure over the entire surface of a model air-screw blade. In this case the air-screw was made of walnut, and fine steel tubing was let into the surface and made up flush with wax.[1]

§ (7) Measurement of Forces and Moments on Models and Parts.—The measurements of forces and moments on models and parts comprises a very great portion of the experimental work carried out in wind tunnels, and special balances have been devised to meet the particular needs of this class of work. Models under tests are sometimes mounted on the arm of a balance (the main balance), which is placed underneath the wind tunnel and has a vertical arm projecting through the floor of the tunnel into the channel; or they may be suspended by wires from a balance (or balances) placed on the roof of the tunnel. Various special methods are adopted according to the nature of the test, but they generally involve the use of either main or roof balances or both.

The use of a roof balance and wire suspension followed on the discovery of the very large effect on the flow round a model which even a comparatively small supporting spindle might have. Recognising this fact, however, there are still many cases in which the main balance may be used, the model being either supported entirely by a spindle attached to the model and to the vertical arm of the balance, or partially supported by the main balance and partially by wires or other support.

(i.) *The Main Aerodynamic Balance.*—Until recent years the only balance used was that placed beneath the tunnel. This balance was designed so that it could be used to measure forces about three axes perpendicular to one another and the moment about a vertical axis. Auxiliary apparatus, to be described later, enabled moments to be measured about two horizontal axes near the model and at right angles to one another. A photograph of the balance is given in *Fig.* 5, and in *Figs.* 6 and 7 diagrams illustrating respectively the arrangements adopted for the measurement of:

(*a*) Force along and across wind (drag and cross-wind) and moment about a vertical axis.

(*b*) Vertical force (lift).

The balance consists essentially of three arms mutually at right angles and each counterbalanced. The axes of the three arms meet in a point at which a hardened steel centre is fixed, resting in a hardened steel cone carried by a supporting casting. The balance has therefore three degrees of freedom, and measurements can be made directly of the moments about the centre lines of the three arms. The vertical arm passes through the floor of the tunnel and normally carries the model at its upper extremity. The upper part of this arm can be rotated about its vertical axis with reference to the rest of the balance, the amount of rotation being observed by a circle divided into degrees and subdivided to $\frac{1}{10}°$ by a vernier. The remaining two arms of the balance are horizontal and respectively parallel and perpendicular to the wind direction in the tunnel. The forces on the model are counterbalanced by weights hung on scale pans at the ends of these arms, fine weighing being secured by riders sliding along divided scales on the arms. The couple about the vertical axis is measured by means of a bell-crank lever carried on the supporting casting and connected with the counterbalance arm of the cross-wind beam by means of a horizontal strut and C-spring. It is theoretically

[1] A full description of the experiments and apparatus may be found in the report to the Aeronautical Research Committee ("An Experimental Investigation of the Nature of the Air Flow around an Airscrew," by A. Fage and R. G. Howard, *R. and M.* No. 565). The measurement of distribution of pressure over an airship model has been described by Pannell and Campbell in *A.C.A., R. and M.* No. 246, and over the upper and lower wings of a biplane by Irving, Powell, and Miss Jones in *A.C.A., R. and M.* No. 355. See also "Airships, Experiments on," §§ (26), (27).

possible to make these three measurements at once, but in practice only drag and cross-wind force are measured simultaneously, and while this is being done the balance is prevented from rotating by means of a strut and C-spring placed between the cross-wind counterbalance arm and a fixed point on the supporting casting. When moment about a vertical axis is measured the balance is prevented from swinging by taking part of its weight on a spring-loaded point vertically under the main supporting point. The sensitivity of the balance is adjusted by the addition of weights near the lower end of the vertical arm, while the rotating upper portion of this arm is provided with four weights, adjustable horizontally, by means of which the centre of gravity of the rotating part (including the model) can be adjusted to lie on the axis of rotation. This is a great convenience in practice, since it eliminates any change of zero reading when the model is rotated to different presentations with respect to the wind direction. The lower end of the vertical arm carries four vanes working in a large dashpot, which thus damp the swinging motions and also the rotation about the vertical axis. The force acting in a vertical direction is determined by weighing the whole balance. This is effected by the use of two subsidiary beams forming a parallel motion (see *Fig.* 7). The lower of these beams rests on a fixed fulcrum and carries at one end a steel centre, which engages the point at the lower end of the vertical arm of the balance. The upper beam, resting on a fixed fulcrum vertically above that of the lower, engages with a point about an inch above the main balance point. The lower beam has a fixed counterbalance weight which balances the greater part of the load, while the upper beam carries a scale pan and rider for the actual weighing. These two beams are easily removed and are only in place when vertical force is being measured. In the earlier balances vertical force was measured on a single beam, to which the force was transmitted by a vertical rod carrying the model and sliding inside the upper portion of the balance, which was then clamped in a fixed position. Small rollers allowed this sliding motion but prevented rotation. This plan was abandoned in later balances in favour of the scheme above described, as it was found that any considerable moment about the vertical axis introduced friction at the rollers of such magnitude that the desired accuracy of vertical force measurement could not be obtained.

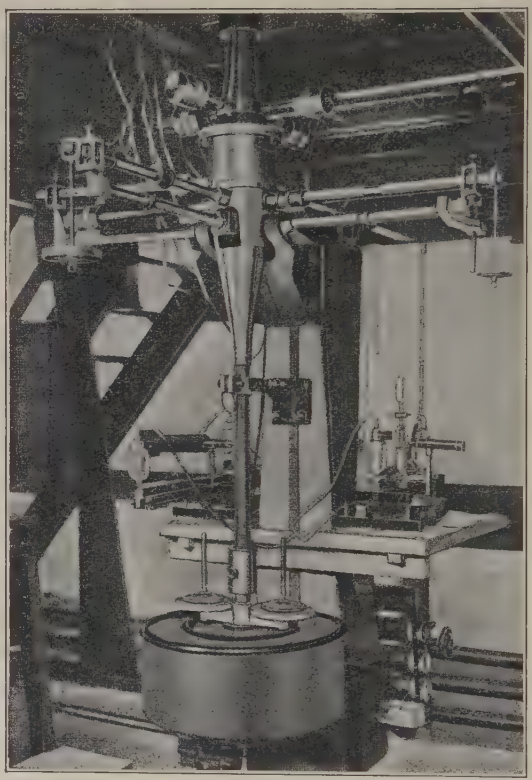


FIG. 5.

With regard to the mechanical construction of the balance, the main portion carrying the weighing beams is a hollow gun-metal casting, into which is screwed a circular plate carrying the main supporting point at its centre, and the upper point for the vertical force apparatus on a bridge piece. The rotating upper part of the vertical arm is also cast in gun-metal, and at its upper end, just below the tunnel floor, ends in a screwed portion to which can be fitted rods of varying length, so that models of varying size can conveniently be held at the centre of the tunnel. The two horizontal weighing beams are of steel, and below each is a similar fixed beam carrying at its outer end a pair of stops to limit the swinging of the balance, and a cross-wire, by reference to which the equilibrium position of the weighing

beam is observed by means of a small mirror on the latter. The lower extension of the vertical arm carrying the damping vanes and stabilising weights is formed of steel tube, into the lower end of which is screwed the point used in yawing moment and vertical force measurements. The whole balance is supported on a heavy iron casting bolted to a concrete foundation, thus securing rigidity and freedom from vibration. A clamp is provided by means of which the balance can be locked in its equilibrium position when not in use or when models are being adjusted. The leverages from the main point to the scale pans and centre of tunnel are not equal, and for convenience in use the weights are marked in such a way that any given weight will balance a force acting horizontally at the centre of the tunnel and equal to the marked value. Flow of air into the tunnel at the point where the balance enters is prevented by an oil seal (see *Fig.* 7). The vertical force due to the difference of pressure on the two sides of this seal must be measured and allowed for when the vertical force on a model is being determined.

Accuracy of construction is of great importance. In particular, the vertical arm of the balance must be within $\frac{1}{60}$th of a degree of the true vertical if the largest horizontal force met with is not to produce appreciable errors in the moment about the vertical axis. This adjustment is easily secured in practice by altering the lower point until a large weight hung on either beam produces no change in moment about this axis. The axis of the rotating upper portion of the balance must be always in line with that of the lower portion. This is best attained when the balance is under construction by fixing one part rigidly on a convenient support and rotating the other part upon it, when the extreme point of the rotated part should remain at a fixed point in space during rotation. The two main weighing beams must be at right angles within $\frac{1}{20}$th of a degree, in order that in the measurement of lift and drag the latter may not be in error by more than 1 per cent by the introduction of a sine component of the former. In setting up the balance the drag beam must be parallel to the direction of the wind within the same limits for the same reason. This is attained by testing an aerofoil for lift and drag by holding it in the balance chuck by a spindle screwed first into one end of the aerofoil and then into the other. If the two sets of readings agree, it follows that the line from which angles were measured, and also the drag beam, are parallel to the wind direction. If the two sets do not agree the observed differences of drag enable the angle between

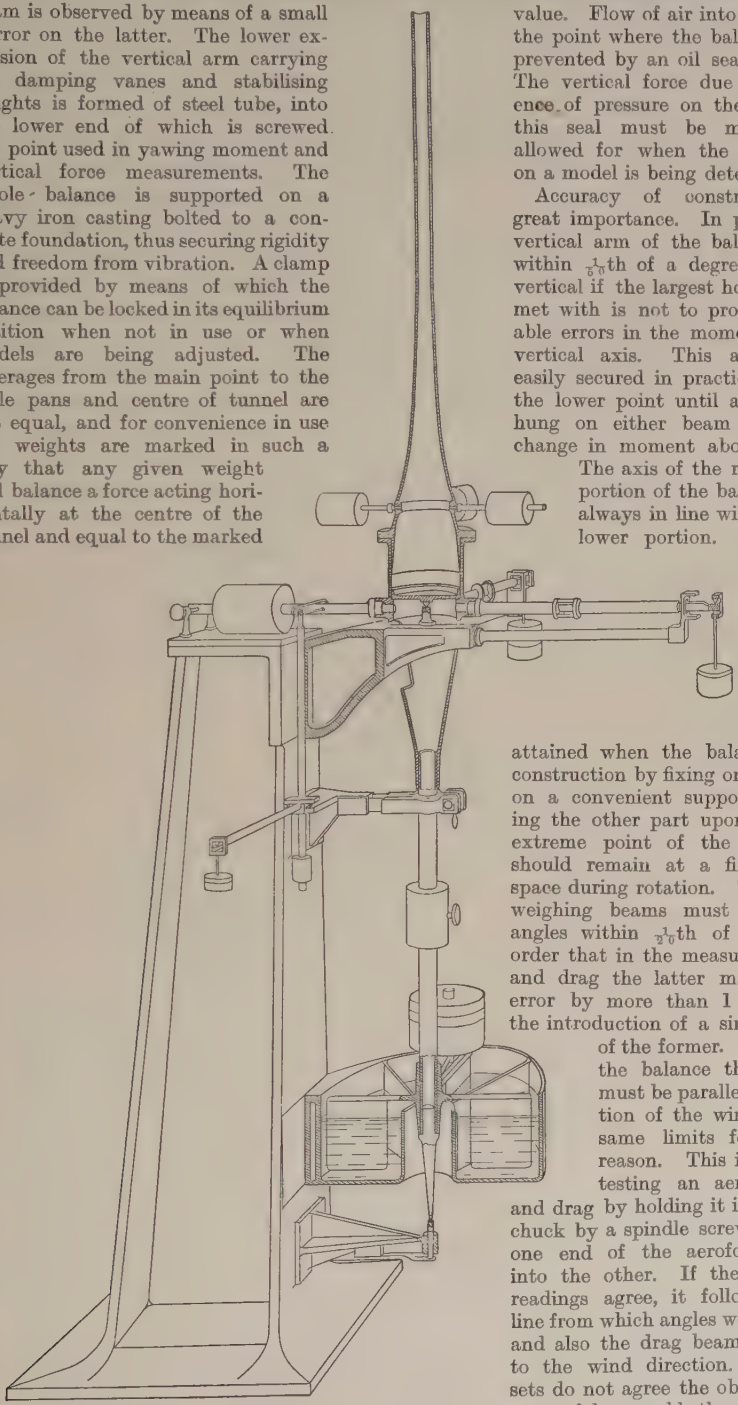


FIG. 6.

the drag beam and the wind direction to be calculated.[1]

(ii.) *Models supported by a Spindle on the Main Balance.*—It is generally the most convenient method of test, if it may be adopted, to mount the model directly on the main balance by means of a spindle. Difficulty arises in certain cases where it is not possible to obtain the necessary strength and rigidity of support without the dimensions and form of the supporting spindle becoming such that there is considerable interference with the air flow round the model, while at the same time the resistance of the part of the spindle which is exposed to the wind becomes possibly as large as the resistance of the model itself. Both resistance and interference of spindle are often difficult quantities to measure accurately and conveniently. The measurement of lift and drag of an aeroplane body, for example, is not a case in which difficulty is likely to arise owing to either spindle resistance or interference. Aeroplane bodies are usually not very good aerodynamic shapes, and the resistance of the spindle, and interference with the model, as well as the interference of the model with the spindle, are usually quite small compared with the resistance of the body. In such a case it is usually sufficiently accurate, in correcting the results for spindle, simply to remove the body from the spindle and measure the resistance of the spindle alone. In the case of an aerofoil, however, which may be tested for lift and drag by being mounted on end on a spindle, the resistance of the spindle may amount to as much as about 50 per cent of the minimum drag of the aerofoil, and there may be considerable interference between aerofoil, spindle, and guard. If the length of spindle exposed is reduced, interference of guard on aerofoil becomes excessive, so that there is no way out of the difficulty here. When comparative results only are required a certain amount of spindle resistance and interference is often not objectionable, but when absolute results are required a very careful determination of both resistance and interference has to be made for such a case as an aerofoil. A method of doing this, which has been successfully applied to an aerofoil, is to attach to the model a second spindle exactly similar to the first, duplication of the guard also being made in the manner shown by *Fig.* 8. The method takes account of all mutual interferences, the only assumption made being that disturbance of flow caused by spindle and guard does not extend beyond the middle of the aerofoil. As the distances of the two spindles from the point of the balance are not the same, an approximation as to the position of the line of action of the resultant

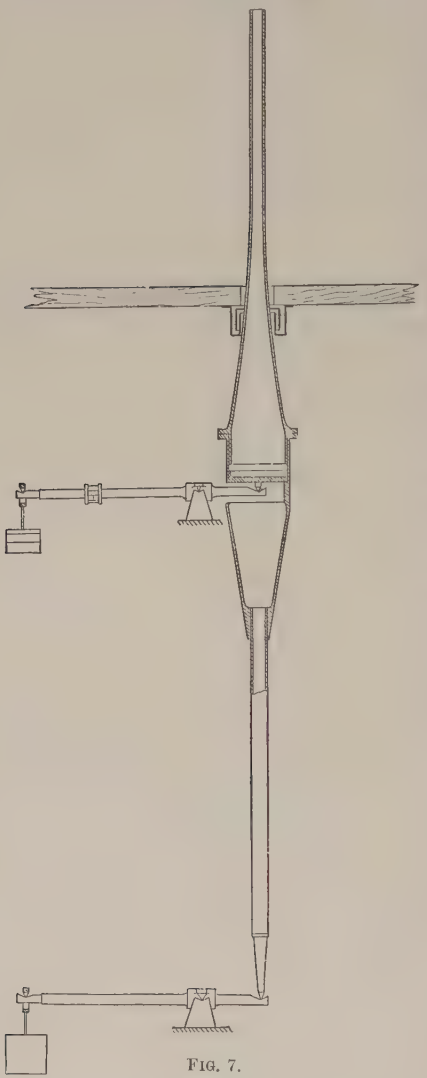


FIG. 7.

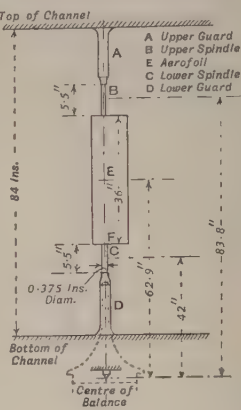


FIG. 8.

[1] For full details of these methods of alignment see *R. and M.* No. 68, *Report of Advisory Committee for Aeronautics*, 1912–13, iv. 59.

spindle resistance has to be made. A determination of spindle resistance and interference by a different method has, however, made it clear that the approximation may be made so as to give no appreciable error. The method referred to consisted of supporting the model with its span horizontal, and taking readings of drag and moment about a vertical axis with and without a " dummy " spindle and guard in position at one end of the aerofoil. In this way the distance of the line of action of resultant spindle resistance and interference is determined.

In measuring the resistance of bodies whose shape is approximately so-called " stream-line," the " dummy " spindle method described above very often breaks down completely, owing to the extensive interference which a spindle may produce in the flow around the model; so that it becomes impossible to add a " dummy " spindle and guard which will have the same effect as the supporting spindle and guard; added to which is the fact that the spindle resistance is a large proportion of the total resistance. The simplest way out of the difficulty in such a case is to support the model by means of a wire or wires from the roof of the channel.

(iii.) *Models supported on Wires : for Measurement of Drag only.*—This method was probably first used by Prandtl of Göttingen, who supported stream-line bodies in the wind tunnel by means of four wires, and transmitted the drag by means of an inclined wire passing through the side of the wind tunnel to a balance outside. The method has also been employed in other laboratories, the drag being sometimes determined by observing the displacement of the model as a pendulum under the wind forces. At the N.P.L. the wire suspension is used, in conjunction with the existing aerodynamic balance, for drag measurement on stream-line bodies such as airship forms. It was found that though a spindle placed near the centre of length of an airship may introduce interference errors comparable in magnitude with the drag to be determined, yet a thin stream-line spindle placed an inch or so behind the tail of the model produced no appreciable interference effect. The model was accordingly supported on one or, more generally, two wires placed near its centre of gravity, and a small steel spike or " sting " was fixed in the tail of the model, projecting about an inch. This spike pressed against the upper end of a small stream-line spindle held in the chuck of the main balance, and was held in contact with this spindle by a light spring (see *Fig.* 9). The supporting wire or wires being arranged to lie in a vertical plane perpendicular to the wind direction, the model is free only to move a small distance horizontally, this distance being limited by the stops on the balance. In effect, the suspending wires and the rear spindle form a parallel motion for small displacements, so that the only force which can be transmitted to the balance is the drag. The fact that the model swings as a pendulum renders the moving system very stable, so that the ordinary method of observing the balance is not sufficiently sensitive. It is almost impossible to reduce the stability of the balance sufficiently by adding weights above the point on which it rocks, and this method has the disadvantage of increasing load on the point and so giving rise to greater errors due to friction. Another method of reducing the stability was to place a strut with pointed ends between the vertical lower part of the balance and the supporting

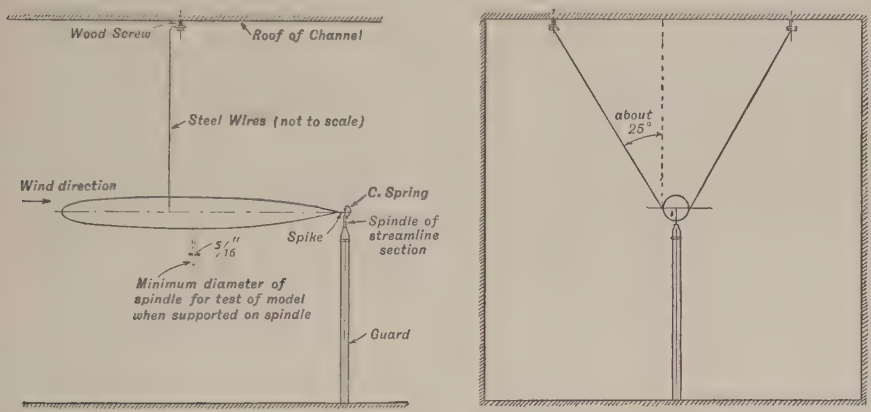


FIG. 9.

casting, and to put this strut in compression by a load hung on the "lift" beam. The stability could be reduced to zero by quite a moderate weight on the lift beam, but a considerable amount of friction was introduced at the points of the strut, which moved through a considerable angle for a small movement of the balance. The method is eminently suitable when measuring a fairly high drag, such as that of an aeroplane body, but does not make the balance sufficiently sensitive for the accurate measurement of the drag of a good stream-line shape. For this latter purpose the best device was found in the use of a microscope to observe the equilibrium position of the "drag" beam of the balance. It was rather surprising to find that even with a magnification of 100 diameters no stickiness due to friction could be detected if the balance point was in good condition, in spite of the fact that the load upon it was of the order of 80 pounds. The method has been in continuous use, and has been found completely satisfactory, the extra accuracy of observation amply compensating the inconvenience of reading by means of a microscope. It is, of course, necessary to determine the drag of the supporting wires and rear spindle. The latter is easily found by supporting the tail of the model by three fine wires so that the "sting" is just clear of the spindle, and observing the drag of the latter on the balance. The drag of the wires may be found by introducing two extra wires symmetrically placed between the model and the floor of the tunnel, and observing the increase in drag due to their addition. Alternatively, a third supporting wire may be placed between the two main wires, and the drag measured first with the three wires in position and then with the outer pair removed and the model supported solely by the middle vertical wire. The method suffers from the disadvantage that the model is liable to swing sideways when supported on only one wire, especially at high wind speeds.

A further important correction to the drag is rendered necessary by the fact that the static pressure along the centre line of the wind tunnel is not constant. The drag is increased by the quantity $\int p d\mathrm{A}$, where p is the static pressure and A the cross-sectional area of the model at any point, integration being taken over the whole length of the model. The variation of p is obtained directly by the use of the static pressure side of the N.P.L. standard Pitot tube, readings being taken with the model removed from the tunnel. A simple graphical integration then gives the desired correction. The magnitude of this correction may be as great as 20 per cent of the drag on an airship model 5 ft. long.

The use of the roof drag balance, to be described later, in place of the ordinary standard balance, has been found to add greatly to the ease of measurement of the drag of stream-line forms. This roof balance is much lighter than the main balance, and it is accordingly easier to obtain the necessary accuracy.

(iv.) *Models supported on Wires for Measurement of Lift, Drag, and Pitching Moment.*—While the method of holding an aerofoil by means of a spindle screwed into one end is quite satisfactory for small aerofoils with square ends, it becomes impossible of application when a large aerofoil with thin wing-tips or when a complete aeroplane model is to be tested, on account of the impossibility of obtaining a sufficiently rigid support without introducing large interferences between the spindle and the wings. A development of the "wires" method of support was therefore sought, which would enable lift and drag measurements to be made on such models. This method, as at present used at the N.P.L., is described below. The model is hung with the wing span horizontal by means of two steel wires attached to the wings about one-third of the chord behind the leading edge, and each about a foot from the plane of symmetry of the model. These wires pass through two small holes in the roof of the tunnel to a balance placed on the roof. This balance is shown diagrammatically in *Fig.* 10. The wires pass over two pulleys about four feet apart, and thence to a winding drum, attached to the moving part of the balance, by means of which the model can be raised or lowered in the tunnel. The two pulleys are carried on a framework rocking about an axis parallel to the line joining them, and carrying the usual weighing beam, scale pan, and dash-pot. The balance therefore weighs the vertical component of the tension in the supporting wires. The rear end of the fuselage of the model (or a "sting" at the trailing edge in the case of aerofoils tested alone) is carried on a small pin joint attached to the lower end of the second roof balance (see *Fig.* 10). This balance can be arranged to read either the vertical or horizontal component of the force acting at the pin joint. It consists of a vertical arm extending downwards into the tunnel (protected by a guard), to which is rigidly attached a weighing beam similar to those of the main balance. This vertical arm is supported on a pair of points so that it can only rotate about a horizontal axis perpendicular to the wind direction and a few inches above the tunnel roof. Weights placed on the scale pan thus give a measure of the horizontal force component at the lower end of the balance arm. The device for measuring the vertical component is very similar to that used in the main balance for vertical force. The pair of

points above mentioned rest in cups carried on one end of a lever at whose other end is a counterbalance, the fulcrum being between the two. An exactly similar lever, engaging with a point at the upper end of the vertical arm, forms with the first lever a parallel motion, so that when the system moves the vertical arm moves up and down in the direction of its length. A scale pan on the upper lever enables the vertical force to be balanced and measured. When drag is measured, the upper lever of the vertical force device is disengaged, and the lower one rigidly locked, so that the balance is then virtually a bell-crank lever turning on a fixed fulcrum. A simple cam device enables the change from drag to vertical force measurement and *vice versa* to be made instantaneously.

It will be readily seen that if the wires are exactly in a vertical plane, and if there were no deflection of the rear balance due to the drag, the sum of the readings of the main lift and the vertical force at the rear pin joint will be the total lift on the model, while the horizontal component measured on the rear balance will be the drag. As the lift has been measured in two parts, there is also sufficient data for the determination of the pitching moment about any axis. The drag due to the supporting wires and rear spindle is found exactly as described under airship drag on wires, except that the two additional wires are introduced between the wings and the upper balance.

The actual procedure is not so simple as described above, on account of the want of absolute verticality of the wires, and the elastic deflection of the rear spindle under the drag load. It is obvious that if the wires are not in a vertical plane the change in their tension due to the lift on the wings will have a horizontal component which will affect the drag balance. The amount of this correction is easily found by hanging a known weight from the main planes in the plane of the wire attachments, and observing the change of zero of the drag balance. The appropriate drag correction for the known actual lift under given conditions is at once calculable. The effect of the slight deflection of the rear spindle under the drag load is mainly to change slightly the inclination of the wires, and so to introduce an error in the drag reading equal to the total tension in the wires multiplied by the sine of the above small change in inclination. This correction can be calculated from a knowledge of the weight of the model, the lift, and the rigidity of the spindle, but a better method is to calibrate the drag balance directly by applying a known horizontal force to the model, and observing the drag reading. This is not strictly correct, as it ignores the effect of lift due to the wind as affecting the total tension in the wires. At moderate wind speeds this lift is of the order of one-fifth of the weight of the model, and as the whole correction is of the order of one per cent it can be neglected. At high wind speeds it is advisable to measure the spindle deflection under given load and calculate the correction. It should here be mentioned that the models are supported upside down in the tunnel, so that the wing lift increases the tension in the wires; with the model right way up, this tension would be decreased by the wing lift, and might result in insufficient lateral stability of the system at high wind speeds, even if the force did not become sufficient to lift the model entirely off the supporting wires.

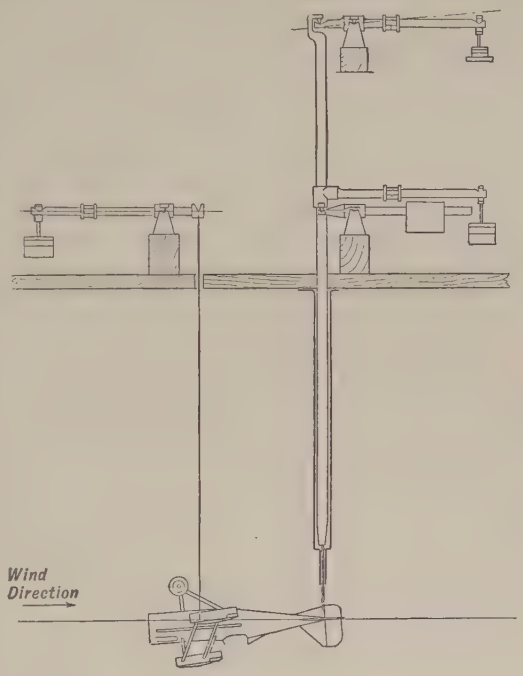


FIG. 10.

For the convenience of any who wish to use this method, the following formulae are appended. They are not exact, but all omitted terms are extremely small, and will not give rise to errors exceeding $\frac{1}{2}$ per cent.

If F = difference of reading of main lift balance with and without wind on,
f = corresponding difference for vertical force balance,
R = corresponding difference for drag balance less resistance of wires and spindle,
W = dead weight on wires without wind on,
w = dead weight on spindle without wind on,
δ = spindle deflection for unit horizontal load,
l = length from pin joint to fulcrum of drag balance,
l' = length of supporting wires,
β = angle between plane of wires and vertical plane;

then

$$\text{Lift} = \text{F} + f.$$

$$\text{Drag} = \frac{\text{R}l}{l + (w+f)\delta - (\text{W}+\text{F})(\delta l/l')} - \text{F}\tan\beta.$$

Pitching moment about any axis whose intersection with the plane of symmetry is defined by the co-ordinates a', b' (*Fig.* 11), is determined by the formula

$$\text{Pitching moment} = \text{L}(a\cos\alpha + b\sin\alpha) - \text{D}(b\cos\alpha - a\sin\alpha) + (\text{R} + \text{F}\tan\beta)(b'\cos\alpha - a'\sin\alpha) - f(a'\cos\alpha + b'\sin\alpha),$$

where a, b are the co-ordinates of the pin joint attachment and α the angle of incidence (see *Fig.* 11). The directions in which forces, co-ordinates, and angles are taken as positive are also shown in *Fig.* 11.

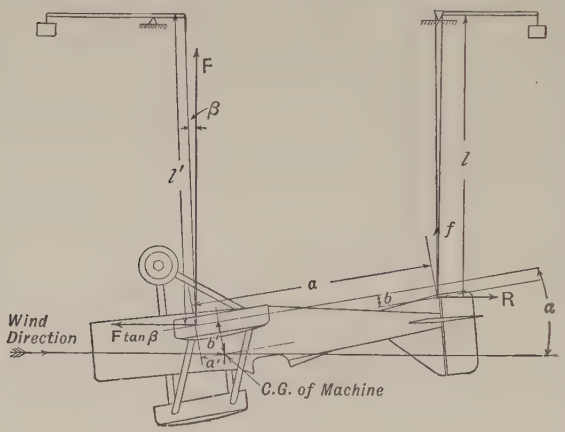


FIG. 11.

(v.) *Miscellaneous Methods; Tests of Control Surfaces.*—Most of the miscellaneous and special methods of measuring forces and moments on models or parts have been adopted in order to make tests of the control surfaces of airships or aeroplanes. The measurements usually required here are the moment on the machine due to given settings of the control surface, and the corresponding moment about the hinge of the control surface. Various methods have been adopted, from time to time, in making these measurements; but, until the development of the "wires" method of test and its application to the testing of control surfaces (as described later), none of these methods can be regarded as having proved to be entirely satisfactory, especially as regards the measurement of hinge moment.

Rolling moments, and in some cases pitching moments also, were measured with the Auxiliary Moments Apparatus, which enabled moments to be measured about horizontal axes in the model along and at right angles to the wind direction. This apparatus has done useful work, not only in connection with the testing of control surfaces but in other connections also. The principle of its action is shown in the diagram (*Fig.* 12), in which an aerofoil is shown attached to the apparatus. The model rests upon a hardened steel point P, which is supported rigidly from the floor of the channel, and it is about axes through this point that moments are measured. Attached to the under side of the model is a vertical spindle S, which makes connection at its lower end to the vertical arm of the main balance through a universal extensible joint J. Thus readings proportional to the moments about the horizontal axes through the point are taken on the beams of the main balance. The method and apparatus are fully described[1] in the reports of the Advisory Committee for Aeronautics. There are two disadvantages to the method. Firstly, it is often not possible so to arrange matters that the point of the apparatus is situated on the axes about which moments are wanted, and in order to obtain moments about the desired axis measurements of drag and cross-wind force have to be made when otherwise they would not be required. Secondly, it is found in practice that it is not always possible to have the vertical spindle of sufficient rigidity to prevent undue angular movement of the model under the wind force without it causing considerable interference to the air flow. It sometimes comes about, therefore, that it is more convenient to rig up a special arrangement whereby the model is supported on points fixing the axis in the model about which moments are actually desired (usually an axis passing through the centre of gravity of the machine), and to transmit the moment either to the main balance or to one of the roof balances, the actual measurement made in either case usually being vertical force. Instances of this method will be given later.

[1] "The Wind Channel, its Design and Use," by J. R. Pannell, *Report A.C.A.*, 1915–16, vii. 32.

If it was desired to measure hinge moment this was generally done by a set of experiments specially devised for the purpose. One simple and obvious method of measurement was to mount the control member on a spindle held in the chuck of the main balance, the main part of the model being held rigidly in correct position relative to the control member, but not making any actual connection with it. This is a method particularly suited for measuring moments on rudders; and if the scale of the model is sufficiently large it is a method which might still be advantageously employed on account of the ease with which it permits the setting of the rudder to any desired angle. When, however, the scale of the model is small, this method suffers from two serious drawbacks.

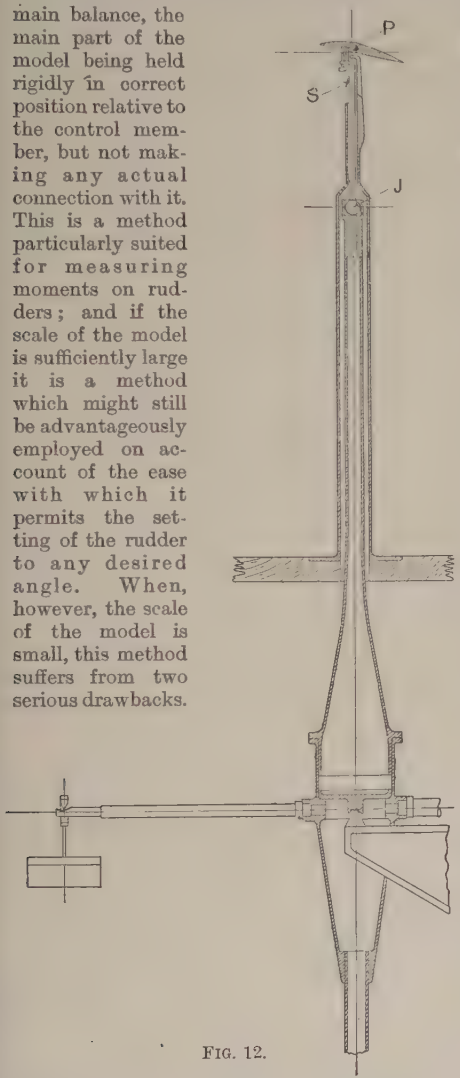


FIG. 12.

Firstly, it is found that it is impossible to obtain a sufficient degree of accuracy when the rudder is small, owing to the limitations imposed by the friction of the points which support the balance, and that some lighter form of balance is required. Secondly, in the small-scale model it becomes difficult so to set up the model that the gap at the hinge is not unduly large and, at the same time, that no fouling takes place between rudder and model. These, as well as the interference with air flow caused by a spindle, are the objections attached to the general method of measuring hinge moment directly on the main balance.

And here it may be as well to emphasise the fact that the question of gap is one always to be seriously considered in any tests on control surfaces, as it has been found [1] that even what might be considered to be a relatively small gap may have quite a large effect on the moment produced by, and the moment on, a control member. For instance, it was found in the case of ailerons on a wing of a 6-in. chord that a gap at the hinge of 0·05 in. reduced the rolling moment by as much as about 40 per cent, while the effect on hinge moment, although not so large, was not inconsiderable.

An example of the method of measuring hinge moment on the main balance is illustrated in *Fig.* 13. Here the measurement was on a flap extending all the length of the rear of an 18″ × 3″ aerofoil,[2] and it will be seen from the figure that although the hinge of the flap is in line with the centre line of the main balance, the flap is not supported rigidly on the end of a spindle, but is freely hinged, by means of point and cone hinges, to the main portion of the wing. Connection between flap and balance is made by a special coupling, designed by Mr. E. A. Griffiths, which, while stiff in torsion, is flexible as to bending. Two of these couplings are provided to allow for any error in alignment of hinge axis and centre line of balance. The main portion of the wing is mounted on a turntable whose axis coincides with the balance axis, so that both angle of incidence of wing and flap angle can be altered from outside the channel and without shutting down the motor—a convenience well worth some pains to obtain when a large number of settings have to be made.

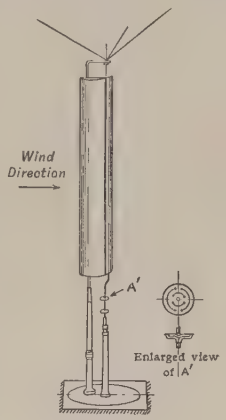


FIG. 13.

An illustration of the "wires" method [3] as applied to measurement of hinge moment on ailerons is given in *Fig.* 14. This figure also

[1] "Investigation on Ailerons," Parts i. and iii., by H. B. Irving, G. A. Hankins, and E. Ower, *A.C.A.*, *R. and M.* Nos. 550 and 651.

[2] "Experiments on an Aerofoil with Flaps extending along the Whole Length," by E. A. Griffiths, *A.C.A.*, *R. and M.* No. 319.

[3] For full particulars see "On a Method of Measuring Rolling Moments and Aileron Hinge Moments on a Model Biplane," by H. B. Irving, B.Sc., *A.C.A.*, *R. and M.* No. 512.

gives the method of measuring the rolling moment produced by the aileron.

The model biplane under test is supported by two hardened steel points P, adjustable in height, and connection to the balance is made through a C-spring and strut by the arm L, which may swivel in the plane of symmetry and may be clamped in any position by a screw. Readings proportional to rolling moments are thus taken on the cross-wind beam of the main balance. Adjustment of the strut for level is made by raising or lowering the points P; for alterations of incidence of the biplane one point is raised and the other lowered.

The ailerons are freely hinged by simple pin hinges, and a pin or "sting" is inserted into the rear edge of each aileron. At the end of this pin is a circular groove, round which a fine wire is given a few turns, and passes upwards to a light roof balance and downwards to near the floor of the tunnel, where a weight is attached to keep the wire taut, the weight being shielded from the wind by a small guard fastened to the floor of the channel. Alternatively, this wire may pass through a hole in the tunnel floor, and the weight attached outside, as shown in the figure. At the upper end the wire passes over a pulley and round a drum on the roof balance. Alteration of the setting of the ailerons is made by rotation of the drum, and the angle which the aileron makes with the wing is determined by sighting from a small removable straight edge on the aileron on to a straight edge with protractor fitted to the wall of the tunnel.

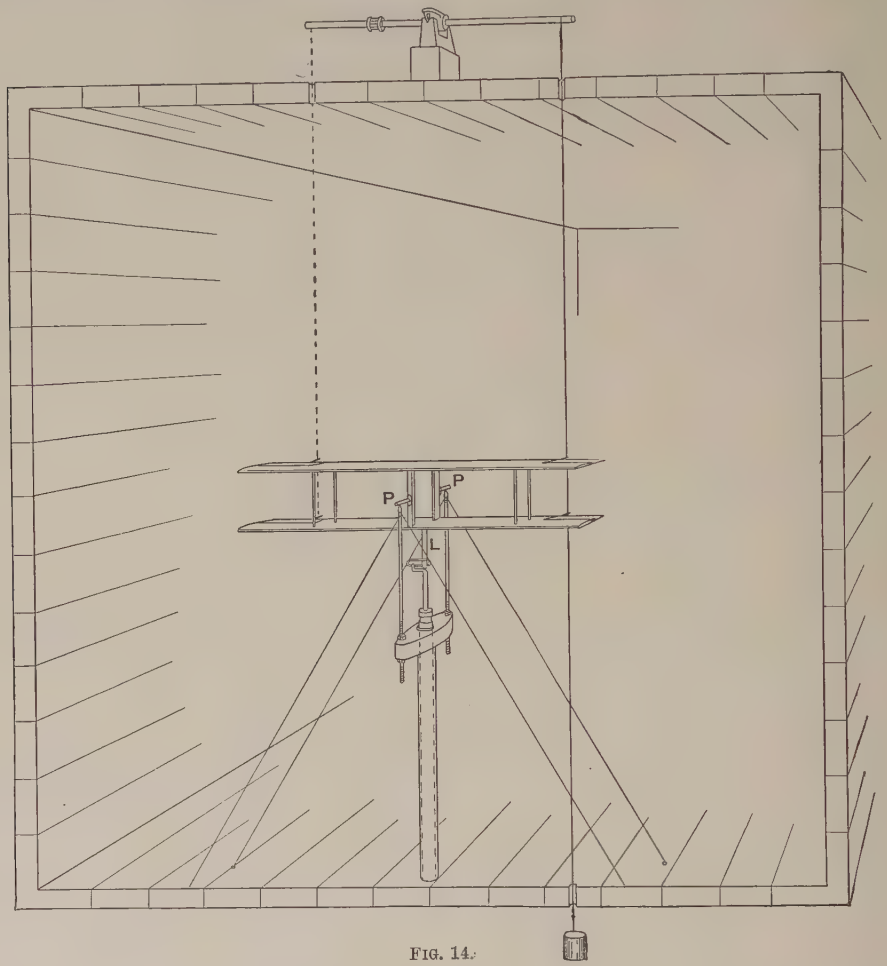


FIG. 14.

Corrections to be applied to the results are those due to the drag of the wire entering into hinge moment reading, to alteration in aileron angle caused by variation in length of the hinge-moment wire under varying tension at different aileron angles, and to angular deflection in roll also causing alteration in aileron angle. These three corrections are,

however, easily applied, and by suitable design may be made quite small.

It has been mentioned that both rolling moment and hinge moment, particularly the former, are affected by the gap at the hinge. The effect may be cut out, however, by completely closing up the gap by a thin film of rubber obtained by applying rubber solution and allowing the solvent to evaporate. Only the minimum amount of solution necessary to form a film of rubber should be applied, or difficulty will be experienced in the measurement of hinge moment owing to "stickiness" of the balance.

It will easily be seen that rolling moment, as well as hinge moment, instead of being measured on the main balance might readily have been measured on a roof balance by means of a wire attached to one of the wing tips of the biplane. This simple method of measuring the moment on the machine is, in fact, the one which will probably find the most general application.

§ (8) Stability Experiments.—It is shown in the article on "Stability" [1] that when an aeroplane is disturbed from a steady flight condition the aerodynamic forces due to the disturbance can be expressed by six equations of the form

$$X = uX_u + vX_v + wX_w + pX_p + qX_q + rX_r,$$

$$L = uL_u + vL_v + wL_w + pL_p + qL_q + rL_r,$$

the other four equations being obtained simply by writing Y, Z, M, and N in place of X or L in the above representative pair.

The quantities u, v, w, p, q, r are the changes (assumed to be small) in the linear and angular velocities produced by the disturbance; X, Y, Z are the forces parallel to the axes, and L, M, N the moments about them.

The coefficients $X_u \ldots N_w$ (with suffix u, v, or w) are known as resistance derivatives, while $X_p \ldots N_r$ (with suffix p, q, or r) are known as rotary derivatives. Thus X_u is the change in the force acting along the X axis due to a change u in the velocity in the direction of this axis; L_r is the rolling moment due to an angular velocity of yaw equal to r, and so on.

The resistance derivatives can all be calculated if the forces and moments on the machine at various angles of pitch and yaw are known. For example, in the simplest practical case of straight flight, with axes of reference parallel and perpendicular to the line of flight, Z_w can be obtained from the slope of the normal force curve plotted against angle of incidence, since w/U is the change of incidence due to a component velocity w along the Z axis. Similar methods give all the derivatives with suffix v or w. Those with suffix u can be obtained from the total aerodynamic forces and couples acting on the machine. Thus if χ represent any one of these forces or moments, it is known that χ is of the form

$$\chi = KU^2,$$

where K is constant to a sufficient approximation.

Hence $$\chi_u = \frac{d\chi}{dU} = 2KU = \frac{2\chi}{U}.$$

It follows that

$$X_u = \frac{2X}{U}, \quad Z_u = \frac{2Z}{U},$$

and so on.

The above calculations give the *magnitude* only of the derivatives, the *sign* depends on the system of axes used.

The rotary derivatives are not so simple to determine. Some of them, such as L_p and L_r, depend almost wholly on the wings, and a good approximation to their value may be obtained if the distribution of the aerodynamic forces along the wing span is known (*e.g.* from pressure plotting experiments). Taking L_r as an example, the effect of an angular velocity r is mainly to augment or diminish the forward velocity of a wing element with respect to the wind. The change in normal force on each wing element can be found, and a graphical integration over the whole wing span will give the total change in rolling moment produced. This is rL_r.

The experimental determination of the rotary derivatives is not so direct as that of the resistance derivatives. The methods used up to the present depend upon measurements of the characteristics of the oscillations of the model when suitably supported in the wind tunnel. It can be shown [2] that, in the case of a rigid body executing small oscillations, a resistance term in the equation of motion proportional to the velocity gives rise to a gradual decrease or damping of the oscillations, the rate of damping depending on the magnitude of the resistance term. Some of the rotary derivatives (L_p, M_q, and N_r) can be determined in this manner; and the formula is developed below. The model is free to oscillate about the desired axis under a spring control, and the derivative is found by measuring the rate of damping of the oscillation.

A second method (for the necessary formulae see (iv.) below) consists in forcing the model to oscillate about one axis by means of a periodic couple about this axis or about an axis at right angles. The period of the forcing couple is varied until the forced oscillation has its maximum amplitude and a relation can be found which gives the derivative in question in terms of this period and the amplitudes of the forces and forcing oscillations. This method can be used to determine

[1] See "Aircraft, Stability of," § (8).

[2] See "Simple Harmonic Motion," Vol. I.

any of the derivatives L, M, N, with suffix p, q, or r.

The derivatives X, Y, Z, with suffix p, q, or r, are in general unimportant in the stability equations, and a rough estimate of their value is sufficient. For example, Z_q, the most important of them, can be obtained with sufficient accuracy by dividing M_q by the distance of the tailplane from the centre of gravity of the machine.

It may here be mentioned that of the 36 derivatives (resistance and rotary) 18 are zero in the case of flight in the plane of symmetry, *i.e.* ordinary horizontal flight, climbing, or gliding. The most important derivatives in this case are X_u, Z_w, M_w, and M_q for longitudinal stability, and Y_v, L_v, L_r, N_v, and N_r for the lateral motion.

Of the two methods, that of measuring the natural damping of an oscillation is the simpler, but the method of forcing the oscillation so that its amplitude remains constant during the experiment is more generally applicable and is the only practicable method for measuring the "compound" derivatives, that is, those involving simultaneous rotation about two axes at right angles to each other.

In the method in which the natural damping is measured it is sometimes found that it is not possible to carry out the experiments over as large a range of wind speed as is desirable. This is due to the fact that the natural damping is sometimes so large at high wind speeds that at the end of one or two complete periods the amplitude of oscillation has become so small that it cannot be measured with sufficient accuracy. In order to obtain observations over a number of swings the amplitude of the initial oscillation may be made fairly large, but if it happens that the derivative which is to be measured varies rapidly with such change of attitude the results of the measurements may not give the true derivative at the mean attitude of the experiment. A way out of the difficulty is to add inertia to the model so that the logarithmic decrement of the oscillations is reduced and more observations may be taken. It is not always easy to do this, however. If the inertia is attached near the model and moves in the wind channel it may itself considerably affect the damping and interfere with the flow round the model; if the added inertia is placed outside the channel there is often difficulty in attaching it rigidly to the model. Such difficulties as have been mentioned do not occur in the method of forced oscillations, and, since the amplitude of oscillation is constant in a given experiment, the effect of variation of amplitude on the results obtained may be studied. In what follows, an account will be given of the theory and methods employed in the carrying out of these oscillation experiments in the cases of the more important rotary derivatives.

(i.) *Longitudinal Rotary Derivatives.* — Of these the most important is M_q, the rate of change of pitching moment due to pitching. This derivative is generally determined directly by oscillation experiments about the pitching axis through the centre of gravity of the machine, and for an aeroplane, the derivatives of lesser importance, X_q and Z_q, deduced from it. Both X_q and Z_q could, if necessary, be found directly by experiment by making in addition oscillation experiments about axes parallel to, but some distance from, the pitching axis through the centre of gravity. For X_q the axis would require to cut the Z axis and be above or below the C.G., while for Z_q the axis would require to cut the X axis and be forward or aft of C.G. At the present stage of development, however, it is sufficiently accurate to estimate both X_q and Z_q.

In measuring M_q the model is supported so that it can oscillate about its pitching axis under the control of a suitable form of spring. The theory of the method of measuring the natural damping is as follows:

Let θ be the deflection or pitch of the model at any instant, measured from the position of equilibrium,
I the moment of inertia of the oscillating apparatus,
T the periodic time of oscillation of the apparatus,
$\mu\dot{\theta}$ the damping couple due to friction of supporting points or knife edges, if any, hysteresis of springs, etc.,
$k_S\theta$ the controlling couple due to the spring,
$k_W\theta$ the controlling couple due to the wind.

The damping couple due to the wind is $-M_q\dot{\theta}$, positive when q or $\dot{\theta}$ is negative.

Then $$I\ddot{\theta}+(\mu-M_q)\dot{\theta}+(k_S+k_W)\theta=0$$

is the equation of motion for the oscillations.

The solution of this equation is

$$\theta=\theta_0 e^{-\frac{1}{2I}(\mu-M_q)t}\cos\left\{t\sqrt{\frac{k_S+k_W}{I}-\left(\frac{\mu-M_q}{2I}\right)^2}+\epsilon\right\},$$

where θ_0 and ϵ are constants determined by the initial conditions of displacement and velocity. The maximum value of θ at the end of n complete periods from the start is then

$$\theta_n=\theta_0 e^{-\frac{1}{2I}(\mu-M_q)nt}, \text{ very nearly;}$$

θ_0 being the initial maximum displacement,

and $$\log_e\frac{\theta_0}{\theta_n}=\frac{nT}{2I}(\mu-M_q),$$

i.e. $$\mu-M_q=\frac{2I}{T}\cdot\frac{\log_e(\theta_0/\theta_n)}{n}.$$

The quantity $\log_e(\theta_0/\theta_n)$ can be determined from the amplitudes (or the logarithms of the amplitudes) of a number of successive oscillations of the model, obtained by direct observation of a spot of light reflected from a mirror on the model to a scale or from a damping curve record obtained photographically or otherwise.

T is easily found either directly with a stop-watch or from the damping curve.

I is best determined from an observation of the periodic time (T_0) of the apparatus with no wind. We have

$$T_0 = \frac{2\pi}{\sqrt{k_S/I - \mu^2/4I^2}},$$

or, with sufficient accuracy,

$$T_0 = \frac{2\pi}{\sqrt{(k_S/I)}},$$

and therefore $$I = \frac{k_S T_0^2}{4\pi^2}.$$

k_S must be found by calibrating the controlling springs.

An oscillation experiment with no wind will determine a value of μ which may be taken as the damping due to the apparatus, and subtracted from observations of logarithmic decrement with the wind on in order to determine M_q.

(ii.) *Method of Supporting Model.*—In the earlier experiments the model was usually supported in the channel on point bearings carefully made so as to reduce the damping due to friction to a minimum. It was found, however, that this solid damping was often not small compared with the wind damping, and furthermore, that it varied with amplitude, and was apt to vary during the course of an experiment. Its magnitude was also found to depend largely on the pressure on the bearings, which introduced the possibility that it varied materially with the force on the model.

An improvement on the point bearings was made by the adoption of spring supports for the model, of cruciform section, oscillation being permitted by deflection of these springs in torsion. By this means the solid damping was very greatly reduced, being now due almost entirely to hysteresis in the cruciform springs. It was also an easy matter to add inertia to the oscillating portion of the apparatus outside the wind tunnel. It was found later, however, that this could not be done without introducing a serious error of unknown magnitude into the results, because it was not possible to make the connection between model and added inertia sufficiently stiff in torsion to be taken as rigid. Finally, as in several other cases of aerodynamic measurements on models, this method gave place to the "wires" method, which was found to be the most convenient and satisfactory in use: there is practically no interference with the air flow, and the damping with no wind is extremely small. Further, the method lends itself to an easy application of the method of forced oscillations, to be described later, in which, as has been mentioned, there is no difficulty as a result of small inertia of the model.

The "wires" method was first applied to the determination of rotary derivatives by Simmons and Bateman.[1] In this method the axis of rotation is fixed by two wire pyramids attached at their apices to the upper and lower ends of the model, and at their bases to the roof and floor of the channel, as shown in *Fig.* 15. Thus the model is free to oscillate about the vertical axis joining the apices. The oscillations are controlled by springs, S, attached to horizontal or vertical wires connected to the body of the aeroplane near the tail and to the sides of the tunnel, as shown. The amplitude of the oscillations is found by reflection of a beam of light from a concave mirror attached to the model near the axis of rotation on to a scale on the side of or outside the tunnel. It is found convenient to divide this scale logarithmically so that the logs of successive amplitudes may be read off directly.

(iii.) *Method of Forced Oscillations.—Fig.* 15 also shows how the "wires" method has been adapted to the method of forced oscillations. The model, supporting wires, and controlling springs are exactly as before, and there is now added the horizontal forcing spring F shown in the figure. The wire connecting this spring to the model passes through one side of the tunnel and is connected to the end of a horizontal eccentric rod, the eccentric being rotated by an electric motor geared down with worm and worm-wheel reduction. The end of the rod is thus given a definite harmonic motion.

Let $\theta_1 \sin pt$ be the angular motion of the model which would be produced by the eccentric if the spring F were inextensible,
k_S the couple per radian required to deflect springs S,
k_F the couple per radian required to deflect spring F,
k_W the couple per radian due to the wind,
θ the deflection of the model at any instant,
μ be damping coefficient due to the apparatus,
I moment of inertia of the apparatus.

Then the equation of motion for the model is

$$I\ddot{\theta} + (\mu - M_q)\dot{\theta} + (k_S + k_W)\theta + k_F(\theta - \theta_1 \sin pt) = 0.$$

After the motion has become steady, the amplitude of the forced oscillation is given by the particular integral of the above equation, which is

$$\theta = \frac{k_F \theta_1 \sin pt}{\sqrt{\{(\mu - M_q)^2 p^2 + (k_S + k_W + k_F - p^2 I)^2\}}}.$$

If the period $2\pi/p$ of the impressed couple be adjusted until θ has a maximum value θ_0, that is, practically, if resonance be obtained, then $2\pi/p$ is very nearly equal to the period of the naturally damped free oscillations of the model, and

$$p^2 = \frac{k_S + k_F + k_W}{I} \text{ approximately.}$$

Hence $$\theta_0 = \frac{k_F \theta_1}{p(\mu - M_q)} \text{ very nearly,}$$

[1] "A Method for Determining the Rotary Derivatives Mq and Nr," *A.C.A., R. and M.* No. 665, January 1920.

whence M_q can be found, μ being determined by a no-wind test.

The method applied in practice is to set the forcing amplitude θ_1 to a convenient value by means of the variable eccentric and to vary p by altering the speed of the electric motor which drives the forcing system, until a maximum value of θ is obtained. The period $2\pi/p$ is then observed by a stop-watch.

(iv.) *Lateral Rotary Derivatives.* — The methods which have been described for determining M_q may also be applied to the measurement of N_r and L_p, when suitable modifications are made in the apparatus, where necessary. Compound rotary derivatives like N_p and L_r can only be determined conveniently by the method of forced oscillations. For this purpose the model is arranged to be free to turn about two axes at right angles; an oscillation about one axis is impressed upon the model and the consequent forced oscillation about the other axis is observed. The motion about the first axis is constrained to be simple harmonic, and that about the second is controlled by suitable springs. The natural damping of the free oscillations is also required, and must be determined by the method whose principle has been outlined in connection with the measurement of M_q.

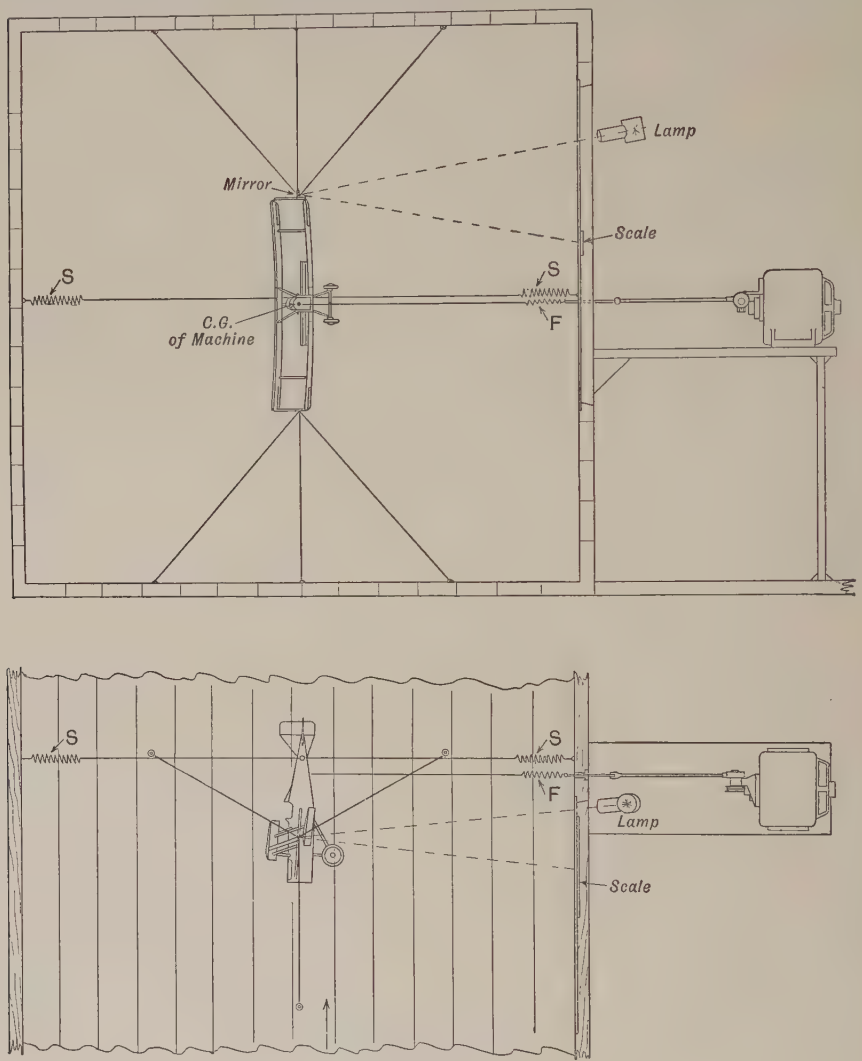


FIG. 15.

The theory of the method is as follows:

Consider the case of L_r or rolling moment due to yawing, and

Let $\psi = \psi_0 \sin \omega t$ be the forced motion in yaw,
$\delta L/\delta \psi$ be the variation of rolling moment with angle of yaw,
K be the stiffness of the springs controlling the roll,
A be the moment of inertia about the axis Ox,
E be the product of inertia with relation to the axes Ox, Oz.

The equation of motion is

$$A\ddot{\theta} + (\mu - L_p)\dot{\theta} + K\theta = \psi_0 \left(\frac{\delta L}{\delta \psi} - E\omega^2\right) \sin \omega t + \psi_0 L_r \omega \cos \omega t.$$

The particular integral gives

$$\theta = \frac{\psi_0}{A} \sqrt{\frac{\left(\frac{\delta L}{\delta \psi} - E\omega^2\right)^2 + \omega^2 L_r^2}{\left(\frac{K}{A} - \omega^2\right)^2 + \frac{(\mu - L_p)^2}{A^2}\omega^2}} \sin(\omega t - \epsilon + \eta),$$

where

$$\tan \epsilon = \frac{(\mu - L_p)\omega}{K - A\omega^2} \text{ and } \tan \eta = \frac{\omega L_r}{(\delta L/\delta \psi) - E\omega^2}.$$

At resonance the amplitude is given to a good approximation when $K = A\omega^2$, and

$$\theta_{max.} = \frac{\psi_0}{\mu - L_p} \sqrt{\left(\frac{1}{\omega}\frac{\delta L}{\delta \psi} - E\omega\right)^2 + L_r^2}.$$

The value of $\delta L/\delta \psi$ is obtainable by a direct measurement of rolling moments at various angles of yaw, and if E can be made zero by suitable additional masses, the value of L_r is calculable. It is found in practice that it is difficult to eliminate E completely, and that with a model having a large dihedral angle $\delta L/\delta \psi$ is so large that its effects mask those of L_r and leave little accuracy in the determination of the latter. The best experimental method is to adjust the period of the forcing oscillation until the motion, the resultant of the forced and forcing oscillations, as observed by means of a beam of light reflected from a mirror on the model, is rectilinear, *i.e.* until the phase difference between the roll and yaw is zero. This gives the relation $\epsilon = \eta$, for if $\epsilon = \eta$, both the forcing motion given by ψ and the forced motion given by θ are proportional to $\sin \omega t$; thus we obtain

$$\frac{\mu - L_p}{K - A\omega^2} = \frac{L_r}{(\delta L/\delta \psi) - E\omega^2},$$

and if the value of $K - A\omega^2$ from the above is substituted in the expression for θ, we obtain

$$\theta_{max.} = \psi_0 \frac{L_r}{\mu - L_p},$$

both E and $\delta L/\delta \psi$ being simultaneously eliminated. It is therefore only necessary to measure the angle which the straight line obtained makes with the axis of θ roll, and if this angle is β we have the simple relation

$$L_r = (\mu - L_p) \tan \beta.$$

A similar method may be deduced for any of the compound rotary derivatives.

Care must be taken that the supporting wires are under considerable tension, or errors will be introduced due to strains in the supports under the varying forces acting on the model.

The use of the whirling arm for the measurement of certain rotary derivatives which have hitherto proved difficult to determine by the method of oscillations is a possibility worthy of serious consideration. The advantage of using the arm would be that a steady value of q or r could be obtained and the derivatives more easily determined from the experimental observations, provided that the apparatus for the measurement of forces and moments could be made to work satisfactorily and that complications arising from centrifugal force would prove surmountable.

(v.) *Auto-rotation.*—Before leaving the subject of stability experiments some notice should be given to a method of experiment of which use has only recently been made. It was suggested by Professor Bairstow that the manœuvre known as spinning might in its essentials be imitated in the wind channel by mounting an aerofoil so that it was free to rotate about a horizontal axis in its plane of symmetry. An aerofoil so mounted and set at an angle of incidence greater than the critical should exhibit auto-rotation, that is, it should continue to rotate in either direction when once started. It has been found that auto-rotation does actually take place, and that the speed of auto-rotation is in rough agreement with that calculated from pressure distribution data, and also that it corresponds roughly with the observed spinning speeds of aeroplanes. The method cannot, however, be used to predict the spinning speeds of an aeroplane, since the speed of auto-rotation depends upon the mean angle of incidence, and the angle of incidence at which an aeroplane spins depends upon the nature and efficiency of the control surfaces and is not easily determined. At the same time, the method promises to give useful qualitative results, perhaps more in connection with the difficulty of controllability at low speeds caused by the tendency of an aeroplane to rotate about a roughly horizontal axis when stalled, rather than in connection with rate of spin. Thus, if it is found that one model does not begin auto-rotation until it reaches a larger incidence than another, it may be considered that the former possesses an advantage over the latter as regards controllability at low speeds. But any conclusion in this direction can, for the present, be regarded only as tentative.

§ (9) Experiments on Air-screws.—Experiments on air-screws usually involve measurement of thrust and torque at known revolutions and wind speed. Both whirling arm and air-screw balance have been used for the purpose.

In the former the air-screw is mounted on a dynamometer at the end of an arm of about 30 ft. length, and forward speed is obtained by rotation of the arm about a vertical axis. The air-screw balance[1] is used in conjunction with a wind channel, the air-screw being rotated in the channel by a motor placed on top of the channel. Both motor and air-screw are mounted on a single point, and there are balance arms along and across the wind direction as in the main channel balance. This apparatus, besides being now the standard apparatus for measurement of the performance of an air-screw by itself, has been used to determine the effect of the presence of various aeroplane bodies on the performance of the air-screw, and at the same time the effect of the air-screw on the resistance of the bodies. In order to do this the model body is made hollow and in halves so that it can be mounted in correct position relative to the air-screw, but quite independently of it. The performance of the air-screw is then measured in the usual way, and the drag of the body is measured on the main balance. Such a method is the one which would be adopted for experiments made in, say, a four-foot channel: in a seven-foot channel it has been found[2] possible to make the model body large enough to enclose the electric motor which drives the air-screw, thus getting rid of interference due to the column supporting the air-screw bearings from the motor and balance. Special means have in this case to be adopted for measuring the performance of the air-screw. This has been done by mounting motor and air-screw on two steel points, fixing an axis along the wind direction, and transmitting the torque through an arm on the under side of the motor to the main balance. For measurement of thrust the two points are lowered and motor and air-screw become suspended on four wires, forming two "V's," attached at their upper ends to the roof of the channel; thrust can then be measured on the drag beam of the main balance. The method is fully described in the report of the Advisory Committee for Aeronautics already referred to, by Fage and Collins, while the method in which the air-screw roof balance is used is described in an earlier report.[3]

E. F. R.
H. B. I.

[1] See "Description of Apparatus for Measurement in a Wind Tunnel of the Performance of an Airscrew," by A. Fage and H. E. Collins, *Report of Advisory Committee for Aeronautics*, 1917–18, x. 54.

[2] See E. F. Relf, "An Electric Motor of Small Diameter for use inside Aeroplane Models," *R. and M.* T. 1674.

[3] See "Experiments to Determine the Lateral Force on a Propeller in a Side Wind," by F. H. Bramwell, E. F. Relf, and L. W. Bryant, *A.C.A. Report*, 1913–14, v. 291.

— N —

NITROCELLULOSE, used to reduce the permeability of rubber fabrics. See "Diffusion through Membranes," § (15) (iv.).

— O —

OIL, LINSEED, as a proofing for balloon fabrics. See "Diffusion through Membranes," § (15) (ii.).

— P —

PERFORMANCE DATA OF A REPRESENTATIVE AIR-SCREW. See "Air-screw, The," § (4).

PERMEABILITY, theory of. See "Diffusion through Membranes," § (13).

Measurements of effect of water vapour on. See *ibid.* § (11).

Of balloon fabrics. See *ibid.* § (4).

Of rubber films by various gases. See *ibid.* § (12).

Of rubber-proofed balloon fabrics. See *ibid.* § (10).

Of stretched-rubber films. See *ibid.* § (10).

PERMEABILITY DETERMINATIONS, effect of experimental conditions. See "Diffusion through Membranes," § (9).

PERMEABILITY TESTS of seams and envelopes of fabric in service. See "Diffusion through Membranes," § (9).

PERMEATION of rubber membranes by gases. See "Diffusion through Membranes," § (4).

PITCH, ANGLE OF. See "Aircraft: Explanation of Terms in Common Use"; also "Aircraft, Stability of," § (2) (ii.).

PITOT TUBE: an instrument used for the measurement of wind velocity. It consists of a plain tube with one open end pointing directly into the relative wind. It frequently is used in conjunction with a "static" tube as an air-speed indicator. See "Aircraft, Instruments used in," § (6).

PLANES OF AEROPLANES: the strength of the main planes, tested under four types of loading. See "Aeroplane Structures, Experiments," § (2.)

PRESSURE DISTRIBUTION, the measurement of, on full-scale aeroplanes and air-screws. See "Aerodynamic Research, Full Scale," §§ (18) and (19).

On aircraft. See "Model Experiments in Aeronautics," § (6).

Over an airship hull. See "Airships, Experiments on," §§ (4) and (8).

— R —

RADIAL ENGINES: Dragonfly, Jupiter, Siddeley, Wasp. See "Engines for Aircraft, Air-cooled," § (4).

RATES OF PASSAGE of various gases through stretched membranes. See "Diffusion through Membranes," § (3).

REACTION AT SUPPORTS OF CONTINUOUS BEAMS. See "Aeroplane Structures, Theory," § (9).

REACTIONS AT SUPPORTS OF CONTINUOUS BEAMS UNDER END THRUST. See "Aeroplane Structures, Theory," § (9).

REDUNDANCIES IN STRUCTURES: members or constraints in a rigid frame over and above those required to fix the geometry of the structure. In such frames it is necessary to know the elastic properties of the material of its members before the calculation of the force distribution can be completely conducted. See "Aeroplane Structures, Theory," § (19).

RESISTANCE OF AIRSHIPS: methods for measuring on full-scale airships. See "Airships, Experiments on," § (2).

On models. See *ibid.* § (5).

RESISTANCE DERIVATIVES: the rates of change with the velocity components, relative to the axes to which the motion is referred, of the aerodynamic forces and couples acting on aircraft. They define the aerodynamic characteristics of the aircraft and are used in stability investigations. See "Aircraft, The Stability of," §§ (3) and (4); also "Model Experiments in Aeronautics," § (8).

RIBS, OF AEROPLANE WINGS, design of. See "Aeroplane Structures, Theory," § (13).

Methods of strength tests on. See "Aeroplane Structures, Experiments," § (8).

RIGID AIRSHIP FABRICS. See "Airship Fabrics," § (3).

ROLL, ANGLE OF. See "Aircraft: Explanation of Terms in Common Use"; also "Aircraft, Stability of," § (2) (ii.).

ROTARY DERIVATIVES, determination of, for aircraft models. See "Model Experiments in Aeronautics," § (8).

ROTARY ENGINES: Clerget, Bentley, Gnome, Le Rhone. See "Engines for Aircraft, Air-cooled," § (2).

RUBBER FILMS, permeability by various gases. See "Diffusion through Membranes," § (12).

RUBBER MIXTURE, effect of its composition upon the permeability of balloon fabrics. See "Diffusion through Membranes," § (14).

RUDDER. See "Aeroplane, Component Parts of."

RUDDER BAR. See "Aeroplane, Component Parts of"; also "Aircraft, Stability of," § (2) (v.).

— S —

SEXTANTS FOR AIRCRAFT. See "Aircraft, Instruments used in," § (10).

SIDE-SLIP. See "Aircraft: Explanation of Terms in Common Use."

SILK. See "Aeroplane Wings, Fabrics for," §§ (1) and (12).

SKIN FRICTION, in relation to the resistance of airships. See "Airships, Experiments on," § (8).

SOAP FILMS. See "Diffusion through Membranes," § (15) (i.).

SPAN OF THE WING. See "Aeroplane, Component Parts of."

SPARS, aeroplane, methods of strength tests on. See "Aeroplane Structures, Experiments," § (10).

Bending and design of. See "Aeroplane Structures, Theory," § (10).

Stresses due to lateral bending of. See *ibid.* § (12).

SPEED COURSE employed in the calibration of air-speed indicators. See "Aerodynamic Research, Full Scale," § (4).

STABILITY OF AEROPLANES, as determined by full-scale experiments. See "Aerodynamic Research, Full Scale," § (20).

STABILITY OF AIRCRAFT, AEROPLANES AND AIRSHIPS. Mathematical treatment. See "Aircraft, The Stability of," § (10).

STABILITY OF AIRSHIPS in flight, condition of, satisfied by that in rectilinear flight. See "Airships, Experiments on," §§ (25), (26).

Observation of, on actual flight. See *ibid.* § (16).

STABILITY EXPERIMENTS ON AIRCRAFT MODELS. See "Model Experiments in Aeronautics," § (8).

STAGGER. See "Aeroplane, Component Parts of."

STALLING ANGLE: the angle of incidence at which the lift on an aeroplane wing is a maximum, and beyond which it rapidly drops. See "Aerodynamic Research, Full Scale," § (14).

STALLING SPEED: the minimum speed of an aeroplane, determination of. See "Aerodynamic Research, Full Scale," § (14).

STATIC PRESSURE, variation of, in wind channels necessitating a correction to be applied to the measured resistance of airship models. See "Airships, Experiments on," § (6).

STATIC TUBE TURN INDICATOR: an apparatus employing two "static tubes" for indicating the deviation of aircraft from a straight course. See "Aircraft, Instruments used in," § (4) (i.).

STATOSCOPE, for aircraft: an instrument for showing whether the machine is flying at constant height. See "Aerodynamic Research, Full Scale," § (6), and "Aircraft, Instruments used in," § (1).

STRENGTH OF AIRSHIP FABRICS. See "Airship Fabrics," § (1).

STRENGTH OF FABRICS. See "Aeroplane Wings, Fabrics for," §§ (5)-(10).

STRENGTH TESTS, method of, applied to the main planes of aeroplanes in normal flight, or under a down load. See "Aeroplane Structures, Experiments," § (3).

STRENGTH TESTS in a nose-dive. See *ibid.* § (7).

STRESSES IN FABRIC. See "Aeroplane Wings, Fabrics for," § (10).

STRUTS, design of. See "Aeroplane Structures, Theory," § (14).
Of minimum weight. See *ibid.* § (15).

— T —

TAIL. See "Aeroplane, Component Parts of."

TAIL SKID. See "Aeroplane, Component Parts of."

TAUTNESS. See "Aeroplane Wings, The Doping of," § (3).

TEARING TESTS on fabrics. See "Aeroplane Wings, Fabrics for," § (9).

TEMPERATURE errors of instruments used in aircraft. See "Aircraft, Instruments used in," § (3) (i.).

TENSILE TESTS on fabrics. See "Aeroplane Wings, Fabrics for," §§ (6) and (7).

THREE MOMENTS, THEOREM OF. See "Aeroplane Structures, Theory," § (8).
Extension of theorem to include end thrusts. See *ibid.* § (8).

THREE-PLY RUBBER-PROOFED COTTON: airship fabric consisting of three layers of cotton with rubber between. See "Airship Fabrics," § (4).

THRUST METER, used to determine the thrust developed by an air-screw. See "Aerodynamic Research, Full Scale," § (11).

TRAILING EDGE. See "Aeroplane, Component Parts of."

TURN INDICATOR: instrument fitted to aircraft to show any deviation from a straight course. See "Aircraft, Instruments used in," § (4).

TURNING CIRCLE, determination of, on airships in flight. See "Airships, Experiments on," § (10).
Calculation of, from experiments on models. See *ibid.* § (24).

TWO-PLY RUBBER-PROOFED COTTON: airship fabric consisting of two layers of cotton with rubber between. See "Airship Fabrics," § (4).

— U —

UNDERCARRIAGE (aeroplane), strength tests on. See "Aeroplane Structures, Experiments," § (17).

— V —

V-TYPE ENGINES: R.A.E., Renault. See "Engines for Aircraft, Air-cooled," § (3).

VARNISHES for the protection of doped fabric. See "Aeroplane Wings, The Doping of," § (5).

VOLUME-LOSS, as a method of testing balloon fabrics. See "Diffusion through Membranes," § (5).

— W —

WATERPROOFNESS. See "Aeroplane Wings, The Doping of," § (4).

WHIRLING ARM, as used for aeronautical experiments. See "Model Experiments in Aeronautics," § (1).

Applied to full-scale airscrew research. See "Aerodynamic Research, Full Scale," § (13).

WIND TUNNELS, as used for aeronautical experiments:

British tunnels. See "Model Experiments in Aeronautics," § (3) (i.), (iii.).

French tunnels. See *ibid.* § (3) (ii.).

German tunnels. See *ibid.* § (3) (iv.).

National Physical Laboratory Type. See *ibid.* § (4).

WIND VELOCITY, measurement of, in aeronautics. See "Model Experiments in Aeronautics," § (5).

WING SPARS, design of. See "Aeroplane Structures, Theory," § (10).

Lateral bending of, in plane of wing. See *ibid.* § (12).

WING STRUCTURES, general construction of. See "Aeroplane Structures, Theory," § (2).

WING SURFACES, THE HYDRODYNAMICAL THEORY OF

§ (1) CIRCULATION AND LIFT.—The possibility of flight rests on the fact that a wing or aerofoil moving through the air experiences a lift force at right angles to the direction of motion, and a drag force opposing the motion. The analytical methods of classical hydrodynamics failed to give a satisfactory account of these forces. It appeared that any body in steady rectilinear motion through an incompressible non-viscous fluid would experience no resultant force, but would merely be subject to a couple tending to rotate the body into a position approximately at right angles to the direction of motion. Helmholtz's method of discontinuous surfaces was an attempt to overcome this difficulty; but although this theory leads to the determination of a force acting on the body, it is unsatisfactory numerically, and it is known that the surfaces of discontinuity are unstable and break up into systems of vortices.

From the point of view of aeronautics chief interest is attached to the behaviour of aerofoils which experience a large lift and a relatively small drag. The typical aerofoil section is a long thin shape with a round nose and fairly sharp trailing edge. For simplicity the problem is first treated as one in two-dimensions, and theory then states that the aerofoil will experience a lift L per unit length when moving with velocity V in a fluid of density ρ if there is a circulation[1] K round it, such that

$$L = \rho V K.$$

It can be seen from the pressure distribution round an aerofoil or from observations of the flow pattern that this circulation does exist in fact. The problems to be solved are to account for the origin of this circulation and to determine its magnitude from the shape of the aerofoil.

The origin of the circulation is to be found in the viscosity, however small, of the fluid. In the fluid itself this viscosity generally exerts a negligible effect, but in the immediate neighbourhood of an aerofoil the viscous forces are of importance. The irrotational flow round an aerofoil without circulation is such that very high velocities occur near the sharp trailing edge, and it is in this region that the flow breaks down. Vortices are formed at the trailing edge, and when these vortices have passed down-stream there is a certain circulation round the aerofoil. This process of the formation of vortices continues until satisfactory conditions have been established at the trailing edge. Theoretically it may be stated that the circulation which arises round an aerofoil will be that which gives the most stable conditions of flow, but in practice it is probable that there is always a small oscillation in the value of the circulation due to the continuous formation of weak vortices of alternate sign.

§ (2) TWO-DIMENSIONAL PROBLEMS. WING OF INFINITE ASPECT RATIO.—The problem of determining the magnitude of the circulation round a two-dimensional aerofoil has been discussed by Kutta and Joukowski for the case of certain special aerofoils with sharp trailing edges. The method is that of the conformal transformation of the flow pattern round a circular cylinder, the circulation being adjusted to bring the rear stagnation point into coincidence with the sharp trailing edge of the aerofoil. Joukowski's[2] transformation is

$$\zeta = z + \frac{c^2}{z}.$$

[1] See "Hydrodynamics in its Application to Aeronautics," § (7).

[2] *Ibid.* § (10).

where $z=x+iy$, and is applied to any circle passing through the point $z=-c$. There are, therefore, two arbitrary parameters, representing the position of the centre of the circle, and a doubly infinite series of aerofoils is obtained. The numerical results obtained by this method give a reasonably satisfactory account of the lift of an aerofoil, but there is still no explanation of the drag force. In the case of two-dimensional flow the drag is due entirely to the viscosity of the fluid, and is, of course, a function of the shape of the aerofoil. The name "profile drag" has been applied to this frictional drag force. The viscosity also exerts a slight modifying influence on the circulation and lift, and, in consequence, the observed lift is always slightly less than that calculated on Joukowski's hypothesis. Joukowski's method is capable of extension to more complex transformations and to more complex aerofoils, with the sole limitation that the aerofoil must have a sharp trailing edge. In the case of a rounded trailing edge a new or extended hypothesis would be necessary to determine the magnitude of the circulation.

§ (3) WING OF FINITE ASPECT RATIO.—Passing next to the problem of an aerofoil in three dimensions, it is evident at once that the whole question of the flow pattern needs reconsideration. Since the lift exists there must be circulation round the central portion of the aerofoil, but at a point outside the wing tips there can be no such circulation. In order to conform to the laws of hydrodynamics it is necessary that vortices should spring from the wing tips to continue the circulation system of the wing. If the circulation had a constant value K across the whole span of the wing, there would be a vortex of strength K springing from each wing tip. In fact, however, the lift is a maximum at the centre of a wing and falls off to zero at the tips, and, in consequence, there is a sheet of vortices springing from the trailing edge of the wing. The vortex elements partake of the general motion of the fluid, and so the vortex sheet passes down-stream behind the wing. Owing also to the mutual interaction of the vortices, the sheet tends to roll up into a vortex pair, and is finally dissipated by the action of the frictional forces. The general type of the flow pattern is thus very closely that described by Lanchester in his discussion of this problem.

The theoretical treatment of the three-dimensional problem is due to Prandtl, who has given a first-order solution which is strictly applicable to the case of small lift forces only. In practice, however, it is found that Prandtl's solution is satisfactory for the whole range of forces occurring in flight. To the first order the trailing vortices are straight lines, and their mutual interaction is neglected. The flow pattern is then determinate, and it is found that the effect of the trailing vortex system is to cause a downward induced velocity w at the aerofoil. Thus the effective incidence of the aerofoil element is reduced by w/V, and the line of action of the lift force is rotated through the same angle, giving a drag component $L(w/V)$. Prandtl's method is to work at a definite value of the lift, and, in consequence, the incidence and drag are both in excess of the values found for two-dimensional flow, the formulae being

$$\alpha=\alpha_0+\frac{w}{V},$$

$$k_D=k_{D_0}+\frac{w}{V}k_L.$$

These formulae apply to an element of the wing, and have to be integrated across the span to obtain the final results. The term k_{D_0} represents the profile drag due to viscous forces which can only be determined empirically at present. The name "induced drag" has been given to the other part of the drag force which is due to the action of the trailing vortices. The general formula for the induced velocity w at the point y' is

$$w=\frac{1}{4\pi}\int_{-s}^{s}\frac{d\mathrm{K}}{dy}\frac{dy}{y'-y}.$$

By this method the characteristics of any three-dimensional wing can be worked out when the two-dimensional characteristics of the aerofoil elements are known. It has been found that the minimum induced drag occurs when the induced velocity has a constant value at all the aerofoil elements, and in this case the curve giving the load per unit area across the span of the wing has the form of a semi-ellipse. For a wing of constant aerofoil section and incidence this load distribution is obtained when the wing has an elliptic plan form. In this special case the formulae are

$$\alpha=\alpha_0+\frac{\mathrm{S}}{2\pi s^2}k_L,$$

$$k_D=k_{D_0}+\frac{\mathrm{S}}{2\pi s^2}k_L^2,$$

where S is the area of the wing and s its semi-span.

Owing to the fact that these are minimum results the formulae can be applied with reasonable accuracy to wings whose load grading curves do not differ too greatly from a semi-ellipse. In particular it has been found to be satisfactory in most cases to use these formulae for rectangular wings, and for rectangular wings with shaped tips.

The case of the rectangular wing has been worked out in detail by Betz by the use of

convergent series, and it appears that for a wing of the usual proportions the induced drag is about 5 per cent above the minimum which occurs with elliptic loading. An alternative treatment of this problem has been given by Trefftz, which is based on the conditions existing in the vortex sheet far behind the wing. On the assumption that the trailing vortices continue backwards in straight lines, it can be shown that the downward velocity in this final sheet is exactly double the induced velocity at the wing. In this way the problem is reduced to one in two-dimensions, and is solved by means of potential functions.

§ (4) Complex Aeroplane Structures.—Prandtl's method can easily be extended to analyse the behaviour of complex multiplane structures, and in this work it is frequently sufficient to regard a wing as carrying uniform load, so that the vortex sheet is replaced by a simple vortex pair. For multiplane structures an important theorem has been established relating to the effect of stagger, stating that if the elements of a multiplane plane structure are moved forwards or backwards in the line of flight and adjusted to give the same lift, then the total induced drag is unaltered. By virtue of this theorem it is sufficient to discuss the case of zero stagger only.

In a multiplane structure the induced velocity at an aerofoil element is due partly to its own trailing vortices and partly to the vortex systems of the other wings. Special interest attaches to the case of biplane structures which are most frequently used in aeroplane construction. The planes carry slightly different loads, but the effect of this difference on the induced drag is negligible, and the formulae become

$$\alpha = \alpha_0 + \frac{S}{2\pi s^2} k_L (1+\sigma),$$

$$k_D = k_{D_0} + \frac{S}{2\pi s^2} k_L{}^2 (1+\sigma),$$

where S is now the total wing area of the biplane and σ is a quantity depending on the ratio of the spans of the two wings (s_1/s_2) and on the ratio of the gap (h) to the mean span. The values of σ are given in the following table.

Table I

Values of σ for a Biplane

$\frac{h}{s_1+s_2}$ =	0	0·1	0·2	0·3
$\frac{s_1}{s_2}$=1·0	1·000	0·655	0·485	0·370
0·8	0·800	0·600	0·459	0·355
0·6	0·600	0·485	0·394	0·315

§ (5) Comparison with Experiment.—This theory of induced drag gives a good account of the differences observed in the lift and drag forces of monoplane wings of different aspect ratio and of various types of biplane structure. It has been tested in a variety of cases, and has given satisfactory results in all cases, with the exception of a few peculiar aerofoil sections. It has also been applied with success to the case of certain complex multiplane structures. As an example of the magnitude of quantities involved, tables are given below of the incidence, drag, and lift-drag ratio for a typical aeroplane. The four columns give the values for two-dimensional flow, for a monoplane of two different aspect ratios (6 and 12), and for a biplane of aspect ratio 6 and of unit gap chord ratio.

Table II

	Two Dimensions.	Monoplane. A=12.	Monoplane. A=6.	Biplane.
		Angle of Incidence		
k_L=0·1	−0·7°	−0·4°	− 0·1°	0·2°
0·2	0·7	1·3	1·9	2·6
0·3	2·6	3·5	4·4	5·4
0·4	4·8	6·0	7·2	8·6
0·5	7·4	8·9	10·4	12·1
		Drag Coefficient		
k_L=0·1	0·0115	0·0120	0·0126	0·0132
0·2	0·0086	0·0107	0·0128	0·0152
0·3	0·0087	0·0134	0·0182	0·0236
0·4	0·0114	0·0199	0·0284	0·0380
0·5	0·0158	0·0290	0·0423	0·0573
		Lift-drag Ratio		
k_L=0·1	8·7	8·3	7·9	7·6
0·2	23·3	18·7	15·6	13·2
0·3	34·5	22·4	16·5	12·7
0·4	35·1	20·1	14·1	10·5
0·5	31·7	17·2	11·8	8·7

§ (6) Application to Wind-channel Experiments.—Another very important application of Prandtl's theory relates to the interference of the walls of a wind channel on the forces experienced by a model wing under test. The interference is calculated by a method of images chosen so as to give zero normal velocity at the walls of the channel, and it appears that the drag measured in a channel with fixed walls is always too small. The formulae for the corrections to be applied to the measured values are :

Square channel : $\Delta\alpha = 0{\cdot}274 \frac{S}{C} k_L \quad \Delta k_D = k_L \Delta\alpha,$

Circular channel : $\Delta\alpha = 0{\cdot}250 \frac{S}{C} k_L \quad \Delta k_D = k_L \Delta\alpha,$

where S is the area of the wing or wings tested and C is the cross-sectional area of the channel. The angle α is expressed in circular measure.

Typical numerical results for a biplane of two equal wings ($6'' \times 36''$) in 4 ft. and 7 ft. channels are given in the table below. It will be seen that the interference is of importance even in the larger channel.

TABLE III

	Free Air.	7-ft Channel.	4-ft. Channel.
	Angle of Incidence		
$k_L = 0{\cdot}1$	0·2°	0·1°	−0·1°
0·2	2·6	2·4	2 0
0·3	5·4	5·1	4·5
0·4	8·6	8·2	7·4
0·5	12·1	11·6	10·6

TABLE III.—*continued*

	Free Air.	7-ft. Channel.	4-ft. Channel.
	Drag Coefficient		
$k_L = 0{\cdot}1$	0·0132	0·0130	0·0127
0·2	0·0152	0·0145	0·0132
0·3	0·0236	0·0221	0·0190
0·4	0·0380	0·0353	0·0298
0·5	0·0573	0·0530	0·0445
	Lift-drag Ratio		
$k_L = 0{\cdot}1$	7·6	7·7	7·9
0·2	13·2	13·8	15·1
0·3	12·7	13·6	15·8
0·4	10·5	11·3	13·4
0·5	8·7	9·4	11·2

H. G.

"WIRES METHOD," for measurement of the aerodynamic forces on a model. See "Model Experiments in Aeronautics," § (7) (iii.), (iv.), (v.).

— Y —

YAW, ANGLE OF. See "Aircraft: Explanation of Terms in Common Use"; also "Aircraft, Stability of," § (2) (ii.).

YAW METER. See "Model Experiments in Aeronautics," § (5) (i.).

DICTIONARY OF APPLIED PHYSICS

PART II.—METALLURGY

A_C AND A_R POINTS—ALLOY SYSTEMS, TYPICAL

— A —

A_C AND A_R POINTS: the temperatures at which changes in the structure of steel take place on heating or cooling. The A_C points refer to changes occurring on heating *chauffage*; the A_R points to changes occurring on cooling — *refroidissement*. See "Iron-carbon Alloys," § (7).

α-IRON. See "Iron-carbon Alloys," § (3).

ABRASIVES, FURNACES FOR MANUFACTURE OF. See "Furnaces, Electric," § (5).

AERO STEELS: steels for aeronautical (aeroplane) construction, mainly alloy steels.

Analysis and mechanical properties of. See "Steels, Special," § (46) (iv.), Tables 14, 15, 16.

AGGREGATES, MOLECULAR, assume first granular and rounded forms when separating to the solid state directly from the gaseous state. See "Solids, The Aggregation of."

AGGREGATIONS IN COLLOIDS, INORGANIC AND ORGANIC, the size and structure of, investigated by the X-ray interference method of Debye and Scherrer. See "Solids, The Aggregation of."

ALLOTROPIC TRANSFORMATION, in a metal, below its freezing-point. See "Metals and Alloys, Micro-structure of," § (5).

With regard to rearrangement of crystalline structure of metals. See *ibid.* § (5).

ALLOTROPY OF IRON. See "Iron-carbon Alloys," § (3).

ALLOY "A," OR "3/20": an alloy containing besides aluminium 3 per cent of copper and 20 per cent of zinc. See "Aluminium Alloys," § (6).

ALLOY SYSTEMS, TYPICAL

§ (1).—There are about thirty-seven metals or metalloids of which there exists a sufficient quantity to enable them to be mixed together so as to obtain enough of the resulting alloys to determine, with a greater or less degree of accuracy, the constitution and properties of the series. If we restrict ourselves to taking these metals together two at a time, we obtain 666 binary systems. Taking the elemental metals together three at a time, we get 7770 ternary systems; while taking four metals together will give rise to 66,054 quaternary systems. These numbers are already considerable, but it must be remembered that some of the alloys of commerce contain more than four constituent metals.

Out of the sixty-six thousand quaternary systems the constitution of only two is even approximately known, while about twenty-five of the ternary systems have had partial equilibrium diagrams published. Of the binary systems somewhat over one-third have been more or less investigated, but of these it is doubtful if there is one diagram which is complete. One reason for this is that the majority of the commercial alloys (the determination of whose constitution has received by far the greater amount of attention) are in general very complicated, while in the case of the simpler alloy systems there has not been the same inducement to thoroughly investigate their constitution. The majority of the binary systems containing alloys of use in the arts have had a large amount of work done upon them, and at any rate the main features of their constitution are well established, while the effect upon the constitution of various small additions of other metals has been partially studied. It is proposed to consider here the constitution of a number of systems which are of interest,

either because of their commercial value, or for some other reason. In all the diagrams the composition is shown as percentage by weight, but in each case a curve is drawn connecting weight percentage with atomic percentage, the former being shown as abscissae and the latter as ordinates.

I. Binary Systems

§ (2) Copper Zinc.—Next to the iron carbon system the alloys of copper and zinc are probably the most important of the commercial metals. The following are the principal alloys in the series:

(i.) *Gilding Metal* (copper content 90 per cent to 95 per cent).—Used chiefly in the manufacture of jewellery.

(ii.) *Pinchbeck*, called after a London watchmaker of the eighteenth century, is also used for making jewellery. It contains 88 per cent Cu.

(iii.) *Tombac* (Cu 86 per cent) is an alloy introduced from Malay. The composition varies considerably, often containing a little tin.

(iv.) *Dutch Metal* (Cu 76 per cent to 84 per cent), also known as Bath metal, can be hammered into very thin sheets, which are used as a substitute for gold leaf, though it tarnishes much more readily. With the addition of a little tin, it is known as Mannheim gold.

(v.) *Bristol Metal* (Cu 75 per cent) and *Prince's Metal* (Cu 73 per cent) are also used for ornamental work. The latter is said to have been first made by Prince Rupert.

(vi.) *Brass* (Cu 62 per cent to 70 per cent).—These form the most important of the copper-zinc alloys. They are used both for casting and rolling, the latter being always done cold, though it is possible, but difficult, to roll them hot. The most usual compositions are (*a*) cartridge brass, which contains 70 per cent of copper; (*b*) "ordinary brass," in which the copper and zinc are present in the ratio of two to one. This alloy is the most generally-used casting brass. (*c*) Common cold-rolled brass (62 per cent Cu). The 70-per cent Cu alloy is the most ductile of the series.

(vii.) *Muntz Metal* (Cu 60 per cent to 62 per cent).—These alloys are rarely, if ever, used in the cast condition, but are hot-rolled. They are stronger, but less ductile, than the brasses, and resist corrosion by sea-water well, being used for sheathing of ships, etc. They are also very suitable for extrusion, though an alloy with a copper content as low as 54 per cent is often used for this purpose.

(viii.) *Brazing Solder* (Cu 50 per cent).—This is the solder used for brazing brass articles. For brazing iron, "ordinary" brass is used.

(ix.) *White Brass* (copper content less than 45 per cent).—These alloys are used for casting statuettes and other ornamental work. In addition an alloy containing 1 per cent of copper has certain useful mechanical properties.

These constitute the principal binary alloys of copper and zinc. There are, however, over 500 specifications for alloys which consist mainly of copper and zinc with additions of other metals. A few of these will be considered under the ternary systems concerned.

The equilibrium diagram of the series has been studied by many workers,[1] and the diagram given in *Fig.* 1 is a composite one made up from the results of these investigators. It will be seen that, in spite of the large quantity of work that has been done, several of the lines are drawn dotted to indicate that they are not definitely established.

The liquidus consists of six branches:

(*a*) Between 100 per cent and 63 per cent copper, crystals of the solid solution α are deposited from the liquid. This constituent is probably the compound CuZn dissolved in copper.

(*b*) From 63 per cent to 39 per cent of copper the primary separation is called β. Here the solvent is probably the compound CuZn.

(*c*) 39 per cent copper to 19 per cent copper. In this case Cu_2Zn_5 is the solvent, and the solution is known as γ.

(*d*) 19 per cent copper to 11·5 per cent copper. The solid solution δ separates from the liquid between these points. The basis of this solution is probably the compound $CuZn_2$.

(*e*) 11·5 per cent copper to 2 per cent copper. The primary separation over this range is the solid solution ϵ. The solvent in this case may be either $CuZn_4$ or $CuZn_6$.

(*f*) The last primary crystallisation η occurs between 2 per cent copper and pure zinc, and the crystals consist of zinc containing—probably—either $CuZn_4$ or $CuZn_6$ in solution.[2]

A somewhat different interpretation of the solutions γ and δ is given by Broniewski, who suggests that the solvent in the former case is $CuZn_2$, while the latter consists of a solution of $CuZn_2$ in the high temperature modification of $CuZn_6$.

The solidus is built up of nine branches, as can be seen in *Fig.* 1. These call for no special comment except to remark that there is no eutectic in the series.

Considering next the various solid solutions,

[1] Roberts Austen, *Inst. Mech. Eng. Proc.*, 1897, xliii.; Shepherd, *Journ. of Phys. Chem.*, 1904, viii. 421; Tafel, *Metallurgie*, 1908, v. 343; Carpenter and Edwards, *Inst. of Metals J.*, 1911, v. 127; Desch, *Inst. of Metals J.*, 1911, v. 172; Hudson, *Inst. of Metals J.*, 1914, xii. 89; Broniewski, *Rev. de Metallurgie*, A, 1921, xcix. 47; Haughton and Bingham, *Roy. Soc. Proc.*; Webber, *Ann. der Physik*, 1920, lxii. 666.

[2] For evidence of the existence of these compounds see Desch, *Intermetallic Compounds*, p. 53.

and the ranges over which they occur, it will be seen that α contains as much as 30 per cent of zinc at 900° C. and 36 per cent of zinc at room temperatures. This range contains all the copper-rich ornamental alloys, and the cold-rolling brasses.

As the α solution becomes more and more saturated the tensile strength of the alloys increases; the ductility also increases up to 30 per cent Zn, and then falls off.

Figs. 5 and 6 in the article on the microstructure of metals and alloys are micrographs of a 70/30 brass.

The area between 36 per cent and 61 per cent of zinc has been the subject of much controversy. Above 470° C. the area can be divided into three fields, $\alpha+\beta$, β, and $\beta+\gamma$. The β field, which occupies the greater part of the area at 850° C., becomes smaller as the temperature falls. Thermal curves taken in this area all show an arrest at 470° C. This has been interpreted by Carpenter as being due to an eutectoid decomposition of β into $\alpha+\gamma$. The resolution of the eutectoid is said to be very difficult to produce in pure copper-zinc alloys, but with the addition of small quantities of other elements resolution is much more pronounced. In opposition to this, it is maintained by Hudson and others that the line at 470° C. is due to a polymorphic transformation in the β, the diagram as drawn in *Fig.* 1 being an approximation to what takes place. Hudson has shown that it is possible to produce apparent β, or β' as he calls it, at temperatures well below 470° C., and that, on passing through this temperature, the β recrystallises, as would be expected in a polymorphic material. This evidence seems conclusive, and the lines are dotted in *Fig.* 1 only because their exact shape and position has not been determined. The $\alpha\beta$ alloys cannot be worked cold, but are always rolled, or extruded, hot. An alloy containing 40 per cent of zinc has the highest tensile strength in the series. *Fig.* 11 in the article on the microstructure of metals and alloys represents a 60/40 Muntz metal in the cast condition.

With more than 49 per cent of zinc the γ phase makes its first appearance. As soon as this takes place the ductility of the alloys falls off very rapidly, and it may be said that pure β represents the limit of the useful alloys.

Between 61 per cent and 69 per cent of zinc the alloys consist of pure γ.

From 69 per cent to 87 per cent zinc the constitution of the series becomes very complicated. Up to about 85 per cent of zinc the first material to separate from the liquid is γ. This separation continues until the temperature has fallen to 700° C., when the reaction

$$\gamma + \text{liquid} = \delta$$

takes place. Although the composition of δ has not been carefully determined, it appears

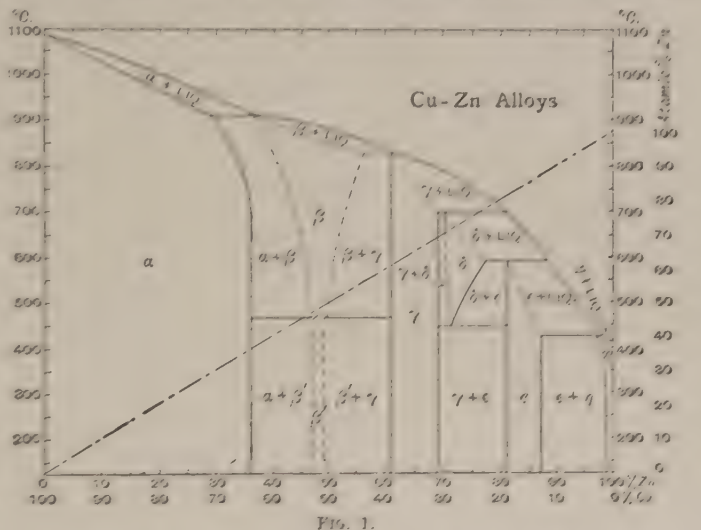


FIG. 1.

that the point at which the reaction is complete lies very near the γ end of the line. To the left of this point the alloys consist of $\gamma+\delta$, and to the right of it $\delta+$liquid. With falling temperature the liquid solidifies as δ in alloys containing less than 77 per cent zinc, and, on cooling being continued, γ or ϵ is deposited from the δ according to the composition, till at 450° C. the eutectoid of $\gamma+\epsilon$ separates.

With more than 77 per cent zinc the reaction

$$\delta = \text{liquid} + \epsilon$$

takes place, pure ϵ being formed at 81 per cent zinc, and excess of δ or of liquid remaining according to whether the zinc content is greater or less than this.

At 425° C. a further reaction takes place, the reacting materials being ϵ and the liquid, and the product being η. *Fig.* 2 shows the

microstructure of an alloy containing 97 per cent zinc, which has undergone this reaction.

Finally, between 98 per cent and 100 per cent zinc, pure η separates over a very small range of temperature.

FIG. 2.—Cu, 3 per cent; Zn, 97 per cent. × 150.

The mechanical properties of some of the more important copper-zinc alloys are tabulated below. It is only possible to include a very few in the table.

TABLE I

COPPER-ZINC ALLOYS

Copper.	Zinc.	Condition.	Maximum Stress. Kilos/Sq. Mm.	Elongation.	Brinell No.
96	4	Cast	28·5	35	50
,,	,,	Annealed	20·5	32	
82	18	Cast	25·5	43	58
,,	,,	Annealed	25·5	45	
70	30	Cast	31·5	48	57
,,	,,	Rolled	50·0	19	
,,	,,	Annealed at 400° C.	39·5	55	
,,	,,	,, 700° C.	31·5	76	
,,	,,	,, 900° C.	29·0	83	
67	33	Annealed	31·5	55	
60	40	Cast	39·5	30	90
,,	,,	Rolled	48·0	37	
,,	,,	Annealed at 650° C.	39·5	48	
55	45	Cast	48·0	25	128
55	55	Cast	9·5	3	
1	99	Rolled	31·5	40	

The figures given in the above table must be regarded in the nature of rough indications only, as the conditions are not specified accurately enough. For example, in the majority of cases the time and temperature of annealing are not stated.

§ (3) THE COPPER-TIN SERIES.—Alloys of copper with tin are not so widely used as those of copper with zinc, partly because the range of useful alloys is much smaller and partly owing to the much higher price of tin compared with zinc. Nevertheless the superior qualities of the bronzes renders their use very desirable in certain cases. In general, however, the alloys used in commerce contain small quantities of zinc. The principal of these are :

(i.) *Coinage Bronze* (copper content, 92 per cent to 96 per cent).—Generally contains about 1 per cent of zinc.

(ii.) *Gun Metal* (Cu 88 per cent to 92 per cent).—This is the most widely used of the bronzes, that variety known as Admiralty Gun Metal containing 88 per cent Cu, 10 per cent Sn, and 2 per cent Zn. In some cases 2 per cent of the tin is replaced by lead. A similar mixture, known as electric bronze, consists of Cu 87 per cent, Sn 7 per cent, Zn 3 per cent, Pb 3 per cent.

(iii.) *Bearing Metal.*—The so-called "brasses" of bearings generally contain between 80 per cent and 88 per cent of copper, 8 per cent to 15 per cent of tin, and 2 per cent to 5 per cent of zinc.

(iv.) *Bell Metal* (copper content 75 per cent to 80 per cent).—Admiralty Standard Bell Metal contains 78 per cent of copper and 22 per cent of tin.

(v.) *Speculum Metal* (copper 66·7 per cent, tin 33·3 per cent).—This was largely used for the manufacture of telescope mirrors. It has now been replaced almost entirely by glass.

As in the case of the copper-zinc alloys, the equilibrium diagram, though widely studied, is by no means fully known.[1] The diagram given in *Fig.* 3 is made up from the results of various workers.

The liquidus, like that of the copper-zinc series, consists of six branches. (Parenthetically, it may be remarked that the liquidus curves, as determined by the various authors, are in extremely good agreement with each other.)

(*a*) Between 100 per cent and 75 per cent of copper the solid solution α is the first material to separate from the liquid. In this substance copper is of course the solvent which, according to a tentative suggestion of Gulliver's,[2] contains Cu_5Sn in solution. It must be remarked, however, that there is little or no evidence for the existence of such a compound, Cu_5Sn being the only definitely established chemical combination known to exist in the series, with Cu_4Sn and CuSn also probably existing.

(*b*) Between 75 per cent and 68 per cent of copper the primary separation consists of β. This, according to Gulliver, may be Cu_5Sn containing copper in solution. According to Broniewski, the compound forming the α and the β solutions is Cu_4Sn and not Cu_5Sn.

(*c*) From 68 per cent copper to 38 per cent copper γ crystals separate, γ possibly being a solution of Cu_5Sn in Cu_5Sn_2, or, following Broniewski, Cu_3Sn in the high-temperature modification of Cu_4Sn, the solvent in the δ solution (see below) being the low-temperature modification of the compound.

(*d*) Between 38 per cent of copper and 8 per cent of copper, the one definitely established compound — Cu_3Sn — separates. This material is referred to as η by Heycock and Neville.

(*e*) The primary separation between 8 per cent Cu and the eutectic point at 1 per cent Cu is the constituent ϵ. According to Gulliver's explanation, this may be the compound CuSn containing Cu_3Sn in solution. This fits in with the earlier work which puts pure ϵ at 65 per cent Sn (50 atomic per cent), but it is difficult to reconcile it with the later work which suggests that pure ϵ occurs between 59 per cent and 60 per cent Sn, as shown in *Fig.* 3.

(*f*) Finally, between 1 per cent and 0 per cent copper, the solution ζ separates. This consists of tin containing minute traces of—probably—CuSn in solution.

The solidus of the system is particularly interesting, as it presents the very uncommon case of a series of alloys, which had completely solidified with fall of temperature, becoming partially liquid on a further fall of temperature, and therefore having a solidus which doubled back on itself. This occurs between 59 per cent and 62 per cent Cu, at 635° C.

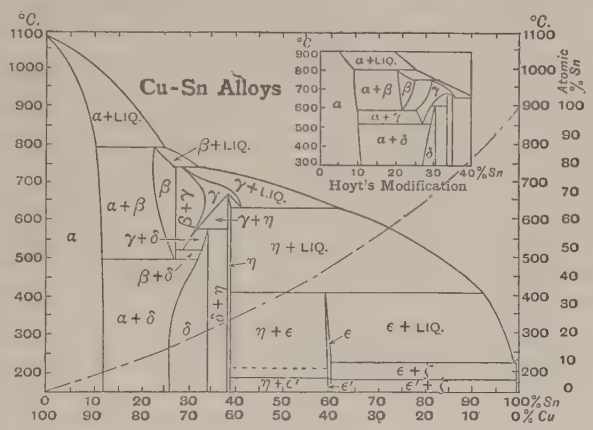


FIG. 3.

The various phase fields may next be considered in some detail. The limit of the α phase at room temperature is about 12 per cent Cu, though this has not as yet been absolutely fixed. It is certainly more than the 5 per cent Cu given by some workers.

Beyond the α field, and between the limits of 790° C. and 500° C., α and β are in equilibrium with each other. On reaching 500° C., however, β decomposes into an eutectoid of $\alpha+\delta$ (β being, probably, a solution based on the compound Cu_4Sn). *Figs.* 4 and 5 are photographs of an alloy containing 20 per cent Sn, the first quenched so as to retain the alloy in the $\alpha+\beta$ form, and the second slowly cooled so as to permit the formation of the eutectoid.

The constitution just described is that which is usually accepted as correct for these alloys.

[1] Le Chatelier, *Comptes Rendus*, April 9, 1984; Roberts Austen and Stansfield, *Third Report Alloys Research Committee*, Appendix 2, 1895, 269; *Fourth Report*, 1897, 67; Heycock and Neville, *Roy. Soc. Phil. Trans.*, 1897, clxxxix. 63; 1903, ccii. 1; Shepherd and Blough, *Journ. Phys. Chem.*, 1916, 515; Giolitti and Tavanti, *Gazz. Chem. Ital.*, 1908, 209; Hoyt, *Inst. of Metals J.*, 1913, x. 235; Haughton, *Inst. of Metals J.*, 1915, xiii. 222; Slavinski, *Journ. Russian Metallurgical Society*, 1913, i. 548; Broniewski, *Rev. de Métallurgie*, 1915, xii. 961; Hoyt, *Trans. Amer. Inst. Mining Engineers*, Oct. 1918; Guervich and Hromalko, *Bulletin of Amer. Inst. of Mining and Metallurgical Engineers*, Aug. 1919, No. 152; Haughton, *Inst. of Metals J.*, 1921, xxv.

[2] Gulliver, *Metallic Alloys*, 2nd ed. p. 260.

One investigator,[1] however, considers that just below 600° C. β breaks up into $\alpha+\gamma$, while at 520° C. γ decomposed, forming $\alpha+\delta$. His interpretation of this part of the diagram is given in the inset of *Fig.* 3. As, however, this means a considerable modification of the accepted diagram between 20 per cent and 30 per cent Sn, in addition to the introduction of the $\alpha+\gamma$ field, and as such modification is as yet based on no experimental evidence, it has not been introduced into the main part of *Fig.* 3, although the evidence for the $\alpha+\gamma$ field appears to be reasonably conclusive.

The whole region between 20 per cent and 40 per cent Sn is exceedingly complicated,

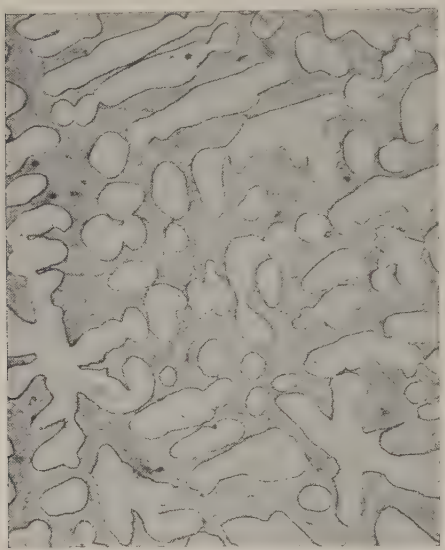


FIG. 4.—Cu, 80 per cent; Sn, 20 per cent. Annealed and cooled at 650° C. ×150.

and as a consequence very uncertain. As an example of its complication let us consider what happens during the cooling of two alloys, one of which contains 30 per cent and the other 40 per cent of tin. At about 765° C. in the former case solidification commences by the separation of β crystals, but at 745° C. these change into γ as a result of the reaction

$$\beta + \text{liquid} = \gamma.$$

At this composition, however, there is not enough β to satisfy the reaction, so that the field immediately below 745° C. consists of γ + liquid. As the temperature falls this liquid deposits more γ until, at about 730° C., the alloy consists entirely of γ. A few degrees lower β makes its appearance once more, the γ breaking up into $\beta+\gamma$, the maximum amount of β separating at about 650° C. Further cooling again increases the solubility of β in γ, and in the neighbourhood of 550° C. it has all dissolved, and the alloy consists once more of pure γ. This, however, almost immediately breaks up into $\gamma+\delta$, while, at about 525° C. β once again makes its appearance, and the alloy consists of $\beta+\delta$. At 500° C. the β undergoes the eutectoid inversion to $\alpha+\delta$, but, with falling temperature, the solubility of δ for α increases and below about 480° C. the alloy consists wholly of δ. It must be admitted that this curious disappearance and reappearance of phases is somewhat unconvincing, and it can only be emphasised that this whole area requires much more work to be done upon it before the diagram can be said to be fully established.

FIG. 5.—Cu, 80 per cent; Sn, 20 per cent. Slowly cooled. $\alpha+\varepsilon$. ×150.

The transformations undergone by the alloy containing 40 per cent of tin are not so complicated, but are nevertheless interesting. Solidification commences by the separation of γ crystals, which continues until a temperature of about 670° C. is reached, when the material is homogeneous γ. A few degrees lower down η (the compound Cu_3Sn) separates. (The sharpness of the cusp on the line indicating the separation of this compound suggests that it is very insoluble in its neighbours, and it has been shown in the figure as having a very narrow range of solubility.) When the temperature falls to 635° C. the γ transforms into η with the formation of liquid.

[1] Hoyt, *loc. cit.*

This liquid persists until the temperature of 415° C. is reached, when a new reaction—η + liquid = ϵ—takes place. On further cooling, two more heat evolutions are found. These will be referred to later.

The solid solution ϵ referred to above exists between about 39 per cent and 99·8 per cent Sn, while alloys in the neighbourhood of 60 per cent Sn consist wholly of this constituent. The ϵ which is formed sheathes the reacting η and protects it from the liquid, thus rendering the reaction very slow. *Fig.* 6 represents an alloy which has been slowly cooled through this range. The light ϵ sheaths can be seen round the half-tone η separating it off from the dark liquid.

All these alloys show a further transformation at 185° C., which appears to be a polymorphic change in the ϵ constituent. In addition to this, alloys between 56 per cent and 60 per cent Sn show another transformation at about 200° C. the meaning of which is obscure.

The eutectic temperature is 227·4° C., and

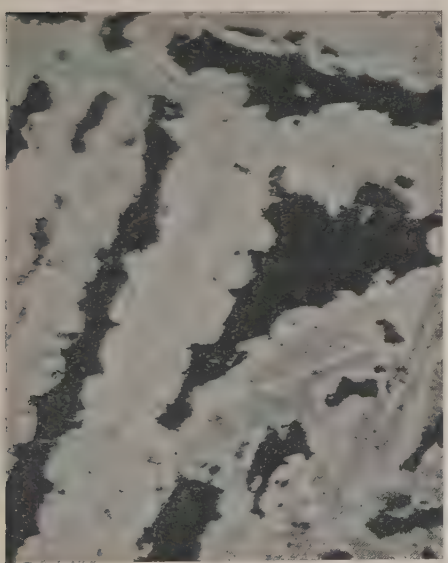


Fig. 6.—Cu, 40 per cent; Sn, 60 per cent. Slowly cooled. $\eta + \epsilon$ + liq. ×150.

the composition of the eutectic is 99 per cent Sn, the phases present being ϵ and tin containing not more than 0·2 per cent Cu in solution.

The alloys which are of commercial use are limited to a small region of the diagram. The mechanical properties of some of these are given in the table below:

Table II

Bronzes

Composition.		Condition.	Elastic Limit. Kg./Mm.²	Maximum Stress. Kg./Mm.²	Elongation. Per cent.	Sclerescope Hardness.
Cu.	Sn.					
91	9	Cast	9·5	24·0	16	8
,,	,,	Quenched at 600° C.	8·0	24·0	23	
84	16	Cast	4·5	24·0	1	20
,,	,,	Quenched at 550° C.	9·5	38·0	6	
79	21	Cast	4·5	19·0	0	50
,,	,,	Quenched at 550° C.	1·5	36·5	3	
75	25	Cast	..	8·0	0	70

§ (4) The Copper-aluminium Series.—The range of useful alloys formed by the addition of aluminium to copper is even smaller than that of the copper-tin alloys, but, unlike the latter system, useful alloys occur at both ends of the series.

Considering first the copper end of the system, the limit of useful alloys is at about 10 per cent Al, or a little more. Of these, the best known is the 10 per cent alloy, which is used in engineering under the name of aluminium-bronze and in jewellery under the name of aluminium-gold. This alloy is very resistant to oxidation, both at ordinary and at high temperatures, though for the latter purpose it is much improved by replacing 1 per cent of the aluminium by iron.

The usefulness of the aluminium-rich alloys extends over a range similar to that of the copper-rich ones, *i.e.* to 12 per cent copper. This latter alloy has been largely used in the construction of aeroplane engine pistons, though it is not the most suitable for the purpose.[1] The aluminium-rich alloys are not, in general, much used by themselves, but are alloyed with a third, or even a third and a fourth, metal to form the "light alloys" which have come so prominently to the front of late years.

The constitution of the copper-aluminium alloys is exceedingly complicated, and, though many workers have studied it,[2] it is still uncertain in several parts. The diagram shown in *Fig.* 7 is a compromise between those given by several workers.

[1] See article on "Aluminium Alloys," § (2).

[2] Guillet, *Rev. de Métallurgie*, Aug. 1905; Carpenter and Edwards, *Eighth Report Alloys Research Committee*, 1907; Curry, *Phys. Chem. J.*, 1907, xi. 425; Gwyer, *Zeits. f. anorg. Chem.*, 1908, lvii. 118; Andrew, *Inst. of Metals J.*, 1915, xiii. 249; Greenwood, *Inst. of Metals J.*, 1918, xix. 55.

The liquidus curve is somewhat more complicated than that of the copper-tin or the copper-zinc system. Between 0 per cent and 10 per cent of aluminium α separates from the liquid. The second branch, between 10 per cent and 17 per cent of aluminium, is the *locus* of separation of β. This is followed by the crystallisation of γ between 17 per cent and 25 per cent of aluminium. Next comes a long branch—up to 44 per cent Al—where δ separates, and this is followed by a very short branch—44 per cent to 47 per cent—which marks the crystallisation of ϵ. From here to the eutectic point at 68 per cent of aluminium the first substance to be deposited from the liquid is the compound $CuAl_2$. The last branch of the liquidus is that along which the aluminium-rich solid solution η separates.

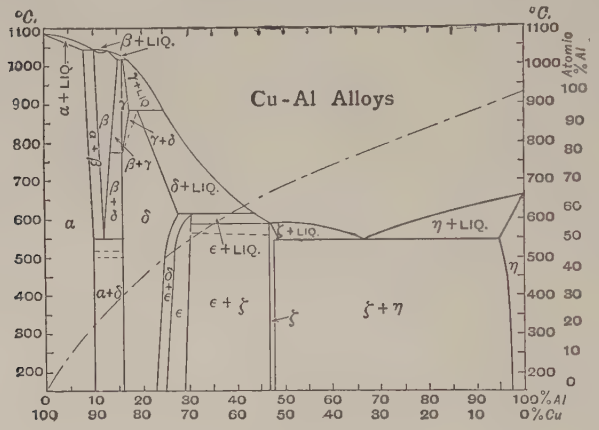


FIG. 7.

The α solid solution exists from 0 per cent to 8 per cent Al at 1000° C., and 2 per cent further at 200° C. The useful copper-rich alloys lie entirely, or almost entirely, within this field.

The area between 10 per cent and 16 per cent Al is somewhat complicated. β, which in the pure state is the compound Cu_3Al, separates from the liquid at first. This compound may dissolve either copper or an aluminium-copper compound richer in aluminium than Cu_3Al to the extent of about 3 per cent of either, at 1000° C., but as the temperature falls the solubility becomes less, until at 550° C. the β undergoes an eutectoid inversion into $\alpha+\delta$. Below this, at about 530° C. and 500° C., two further series of arrest points are shown on thermal curves. Their exact meaning appears to be a matter of some doubt.

The copper side of this area, above the eutectoid inversion, is simple, but the aluminium side is more complex. As the temperature falls, material which is called γ separates from the β; but when a temperature of 775° C. is reached, γ transforms into $\beta+\delta$. Beyond 16 per cent Al there exists a very narrow γ field, and the transformation of this material into δ takes place along a steeply rising line, which meets the solidus at about 880° C. The solidus, at this point, is the peritectic reaction $\gamma+\text{liq.}=\delta$. It will be seen that the δ is formed in four ways. Between 10 per cent and 16 per cent Al it arises from the eutectoid decomposition of β. From 16 per cent to 17 per cent Al it is produced by a transformation of γ. From 17 per cent to 19 per cent Al it arises as the product of the reaction $\gamma+\text{liq.}=\delta$; while between 19 per cent and 30 per cent Al it is formed partly as the result of this reaction, and partly from the solidification of liquid.

It must be admitted that part of this area is not very convincing. On the other hand, the experimental difficulties in making an accurate determination are undoubtedly very great, particularly in view of the fact that it has not been found possible to detect any structural changes accompanying some of the thermal arrests. The line separating $\gamma+\delta$ from δ is not shown by Carpenter and Edwards, and is drawn by Curry almost vertically down to about 550° C. The latter also shows the pure γ field extending down to this point. The existence of the line indicating the decomposition of γ appears to be well established, as well as the shape of the γ field, so that the existence of a $\gamma+\delta$ field is necessary, and the boundary of it is probably not very different from the line shown in the diagram.

The area between 20 per cent and 30 per cent Al is very obscure. Curry's diagram is the most complicated, but it is not theoretically possible to include in it the γ and $\gamma+\delta$ fields as shown in *Fig.* 7, and the diagram given here is a compromise between Carpenter and Edwards' and Curry's.

Between 30 per cent and 47 per cent Al Carpenter and Edwards find, from the thermal curves, a slightly sloping line at about 570° C., but find no structural change accompanying it. The meaning of this line is very obscure, and it is shown dotted in the figure.

Except for this line, the diagram is fairly straightforward beyond 30 per cent Al. The narrow range over which ζ— the compound $CuAl_2$— exists is drawn on the evidence of Carpenter and Edwards. The eutectic point occurs at 67 per cent Al and about 540° C. The limit of solubility of $CuAl_2$ in aluminium —5 per cent at eutectic temperature and 3 per

cent at 200° C.—is obtained from some recent determinations at the National Physical Laboratory.

The mechanical properties of a few of the more interesting alloys are given below:

TABLE III

COPPER-ALUMINIUM

Composition. Cu.	Al.	Condition.	Yield Point. Kg. Mm.^{2}	Maximum Stress. Kg./Mm.^{2}	Elongation. Per cent on 50 Mm.
96	4	Sand cast	5·5	26·0	83
,,	,,	Sand cast, quenched at 800° C.	4·5	26·0	60
,,	,,	Chill cast, quenched at 800° C.	8·0	28·5	81
90	10	Sand cast	19·0	50·0	26
,,	,,	Sand cast, quenched at 800° C.	36·0	79·0	3
,,	,,	Chill cast, quenched at 800° C.	28·0	61·0	22
,,	,,	Rolled	23·5	61·0	18
6	94	Sand cast	9·5	12·5	3
,,	,,	Chill cast	8·5	15·5	5
,,	,,	Rolled	21·0	17·3	33

§ (5) ALUMINIUM-ZINC SERIES.—The most useful alloys in the aluminium-zinc series are those containing 15 per cent to 25 per cent of zinc, though, as in the case of the copper-aluminium series, so here, the binary alloys by themselves are not much used, but form the basis of metals containing one or two other components as well. Some of these are dealt with in the article on "Aluminium Alloys."

The constitution of the aluminium-zinc alloys has been investigated by Heycock and Neville,[1] Shepherd,[2] Ewen and Turner,[3] Rosenhain and Archbutt,[4] and Bauer and Vogel.[5]

The very careful work of Rosenhain and Archbutt renders it probable that their diagram is a very close approach to the truth, as far as the lines shown on it are concerned, though, as pointed out by the authors in a footnote to their paper,[6] theoretical reasoning demands the addition of other lines. They were unable to find experimental evidence for these lines, and therefore omitted them. In order to make the diagram reasonably complete, such lines have been dotted in in *Fig.* 8, which is otherwise the diagram given by Rosenhain and Archbutt.

From the figure it will be seen that the α region is very small, zinc being able to retain only about 1 per cent of aluminium (in the form of Al_2Zn_3) in solution. At 5 per cent Al an eutectic is formed—at 380° C.—between this solution and the Al_2Zn_3, and from this point to about 15 per cent Al the compound separates from the liquid along a rising line. From 15 per cent to 100 per cent Al a new body is the primary separation. This is the solid solution of zinc in aluminium, known as γ. At the temperature of 443° C. this solution reacts with the liquid to form the compound Al_2Zn_3. On the zinc side of an alloy whose composition corresponds to the compound, there will be liquid left over as a result of this reaction, and on the aluminium side there should be γ. This point will be discussed later, and at present consideration will be restricted to alloys containing more zinc than does the compound, which is called β on the diagram. These alloys, on cooling, deposit, at 382° C., eutectic consisting of $\alpha+\beta$. On further cooling the β breaks up once more in accordance with the reaction

$$\beta = \alpha + \gamma.$$

This case of an alloy first depositing γ crystals, which, on a lowering of the temperature, react with liquid to form a compound that itself decomposes to form two constituents, one of which is γ once more, is very interesting, and may be compared with the case of an alloy containing 30 ± 2 per cent Sn and the rest

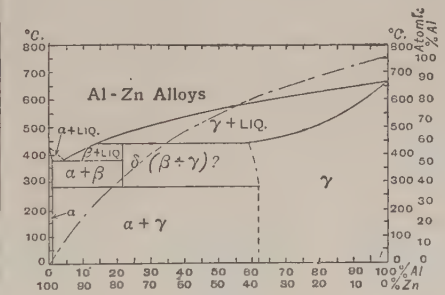


FIG. 8.

copper, in which the primary separation β reacts with liquid to form γ, which, at a lower temperature, deposits β once more. It must, however, be admitted that in the aluminium zinc series the reality of the reaction is proved, while in the copper-tin series it still remains doubtful.

Considering now the case of alloys containing less zinc than Al_2Zn_3, the diagram becomes much more difficult to explain. Rosenhain

[1] *Chem. Soc. J.*, 1897, lxxi. 389.
[2] *Physical Chem. J.*, 1905, ix. 504.
[3] *Inst. of Metals J.*, 1910, iv. 128.
[4] *Roy. Soc. Phil. Trans.*, 1911, ccxi. 43.
[5] *Internat. Zeits. für Metallographie*, 1916, viii. 107.
[6] *Loc. cit.* p. 64.

and Archbutt found a homogeneous field from here to pure aluminium, and called this δ at one end, and γ at the other, as they were unable to distinguish between these two constituents. In *Fig.* 8 a dotted line has been drawn in separating these two fields. This is drawn from the point where the line indicating the reaction

$$\gamma + \text{liquid} = \beta$$

ceases to be horizontal, *i.e.* where the reaction ceases. This point is joined up with the end of the line indicating the decomposition of β as given by the thermal curves, and from this point the line is drawn vertically downwards. It is of course admitted that the evidence for the position of these lines is almost negligible, but they must exist.

There remains the field marked δ to consider. This is explained as being the compound Al_2Zn_3 containing γ in solution. In this case it is the same, from a phase point of view, as β, and there must be a $\beta+\gamma$ field on the diagram, which may, however, be very small. On the other hand, it can be deduced from phase-rule considerations that, below a horizontal line in a binary system, a two-phase field must exist. This demand can be met by one of two assumptions: (1) That the field marked δ really consists of $\beta+\gamma$, the two constituents being so similar that they could not be distinguished from each other. This seems exceedingly unlikely. (2) A more probable suggestion is that a line runs nearly parallel to the line of the reaction $\gamma+\text{liq.}=\beta$, from the point where pure Al_2Zn_3 is formed, finally curving down close to the dotted line forming the boundary of the γ field. Such a line, which might be exceedingly difficult to detect, would form the lower boundary of the $\beta+\gamma$ field. The fact that quenching experiments were carried out in this region to determine the solidus, and that they revealed no duplex structure immediately below the horizontal line, throws doubt on this explanation.[1]

The large field of homogeneous solid solution at the aluminium end of the diagram suggests that alloys containing a considerable amount of zinc would be commercially useable. Practice bears this out,[2] and the following table shows the mechanical properties of a few of them:

TABLE IV

ALUMINIUM-ZINC

Composition.		Condition.	Yield Point. Kg./Sq. Mm.	Maximum Stress. Kg./Sq. Mm.	Elongation. Per cent on 5 Mm.
Al.	Zn.				
89	11	Sand cast	10·0	14·5	8
,,	,,	Chill cast	8·0	16·0	16
,,	,,	Rolled	8·5	18·0	66
84	16	Sand cast	17·5	20·0	4
,,	,,	Chill cast	8·5	18·0	7
,,	,,	Rolled	11·5	16·0	58
74	26	Sand cast	17·5	27·5	2
,,	,,	Chill cast	17·0	28·0	4
,,	,,	Rolled	32·0	37·5	20

§ (6) THE COPPER-NICKEL SERIES. — The four systems so far considered are all markedly complex, while the copper-nickel series presents one of the most simple of types possible. The component metals are completely soluble in each other, both in the liquid and in the solid states. The diagram given in *Fig.* 9 is due

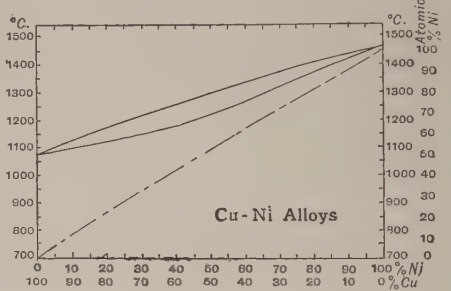


FIG. 9.

to Guertler and Tammann,[2] and from the fact that it may be said to be all α phase it is possible to deduce that the whole series of alloys would be workable, though those in the middle would be likely to be much harder than the constituent metals. It might, further, be expected that the electrical resistivity of alloys containing approximately equal parts of the components would be high, and their temperature coefficient low. All three assumptions are found to be justified in practice. Alloys containing 2 per cent to 3 per cent of nickel have been used for locomotive fireboxes, 12 per cent nickel alloys are used for coinage, and 20 per cent nickel for the casing of rifle bullets. An alloy containing 40 per cent of nickel has a very high electrical resistivity and a low temperature coefficient, and is much used under several

[1] Since this was written the work of Hanson and Gayler, *Inst. of Metals J.*, 1922, xxvii. 267, has shown that β is not the compound Al_2Zn_3 but a solid solution which decomposes eutectoidally at 260° C., that the boundaries of the $(\beta+\gamma)$ field run from about 70 per cent. Zn at about 440° C. to about 80 per cent–35 per cent Zn respectively at 260° C., and that the $(\alpha+\gamma)$ field stretches much further at low temperatures than is shown in *Fig.* 8.

[2] See article on "Alloys, Some Special."

[2] *Zeits. f. anorg. Chem.*, 1907, lii. 25.

names, such as constantan, eureka, etc., in electrical-instrument work,[1] while an alloy which contains 70 per cent of nickel and small quantities of iron and manganese is known as Monel metal, and has certain remarkable mechanical properties.

The chief value of the firebox alloy is that it retains its strength at high temperatures much better than copper.

Monel metal itself is of sufficient interest to justify more than a slight reference. The alloy is one of the few which is not made by melting the components together, but is made by reducing a copper-nickel sulphide ore, which occurs chiefly in Ontario. The average composition of the alloy is

Ni	67 per cent
Cu	29 ,,
Fe	3 ,,
Mn	1 ,,

The mechanical properties claimed by various observers show considerable variation—due probably to variation in composition, as neither work nor heat treatment has much influence on the mechanical properties.

The following are average values:

State.	Yield Point. Kilos/Sq. Mm.	Maximum Stress. Kilos/Sq. Mm.	Elongation. Per cent.
Cast . . .	25	40-46	34
Rolled . .	32	55-63	40-50
Rolled and annealed at 800 C°.	24	55	50

One very important property of Monel metal is that it retains its strength at high temperatures—a rolled bar, tested at 400° C., having a tensile strength of 48 kilos per sq. mm. It is also very resistant to corrosion.

§ (7) Aluminium-magnesium Series.—The aluminium-magnesium alloys form a series which, at first sight, appear most promising for the manufacture of light alloys, owing to the fact that both the constituents are of very low density. Up to the present, however, they have not proved of very much value, though magnesium in small quantities is added to more complex aluminium alloys.

The constitution of the series has been studied by Boudouard,[2] Grube,[3] Eger,[4] and Hanson and Gayler.[5] The diagram reproduced in *Fig.* 10 is taken from the work of the last-named authors.

The diagram has several points of special interest. Attention may first be drawn to the compound Al_3Mg_2, which separates from the liquid at about 450° C. and forms solid solutions over a very limited range. This compound forms eutectics with aluminium and with Al_2Mg_3, and the two eutectic points, which occur at almost exactly the same temperature, are separated, in composition, by a range of not more than 8 per cent. In addition, the maximum distance between the liquidus and solidus in this region is not more than a very few degrees. It is not surprising, therefore, that all the earlier workers failed to find this compound, and that it was only discovered by refined methods of observation and careful study.

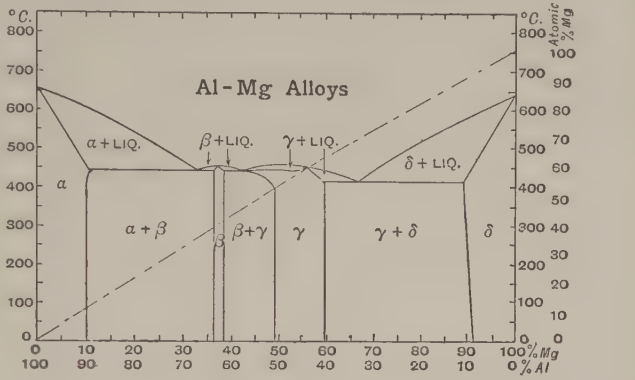


Fig. 10.

Another interesting point in the diagram concerns the compound Al_2Mg_3. This is shown to separate from the liquid at a point which is not on the maximum of the liquidus, but a few degrees lower down, and about 5 per cent of magnesium away from the maximum point. This is the only case known where a maximum on the liquidus does not correspond to a compound, and, while it seems impossible to explain the very concordant observations in any other way than that shown in the figure, it must be admitted that this part of the diagram should be received with a little reserve.

The rest of the diagram is comparatively simple. The solid solubility limits are approximately the same at both ends of the series, *i.e.* each metal is capable of dissolving about 10 per cent of the compound nearest in composition to it. Two compounds are formed, of which one, Al_3Mg_2, has a very narrow range of solid solubility, which is, however, almost unaltered with change of temperature. The other, Al_2Mg_3, has a solubility range of nearly

[1] See article on "Resistance, Standards and Measurement of," § (4), Vol. II.
[2] *Comptes Rendus*, 1901, cxxxii. 1326.
[3] *Zeits. für anorg. Chem.*, 1905, xlv. 225.
[4] *Internat. Zeits. für Metallographie*, 1913, xxix.
[5] *Inst. of Metals J.*, 1920, xxiv. 201.

20 per cent at high temperatures, which falls rapidly to 11 per cent with falling temperature. The two compounds form eutectics with each other and with their constituent metals.

§ (8) Silver-copper Series.—The silver-copper alloys form another very simple series. The diagram (*Fig.* 11) is a typical eutectiferous one, with a comparatively small, and as yet very incompletely determined, range of solid solutions at each end. The liquidus of the system has been determined with extreme

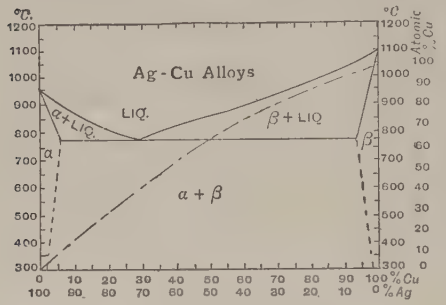


Fig. 11.

care by Heycock and Neville,[1] who also observed the solidus in the neighbourhood of the eutectic point, while Friedrich and Leroux [2] determined approximately the range of the eutectic arrest. It is suggested by Desch [3] that the eutectic arrest as drawn by those investigators is too long, and should stop at about 80 per cent Cu instead of 94 per cent Cu, as shown in *Fig.* 11. The eutectic composition is 71·9 per cent Ag and the temperature 778° C. This has been so carefully determined that it is used as a secondary temperature standard—for example, in the standardisation of thermocouples.

Silver-copper alloys are principally used for coinage. Standard silver is 925 fine—*i.e.* it contains 92·5 per cent Ag and 7·5 per cent Cu—and was the alloy used for coinage till the end of 1920, when, owing to the high cost of silver, it was replaced by an alloy containing 50 per cent Ag, 40 per cent Cu, and 10 per cent Ni. Most Continental coinage is 900 fine, and alloys of this fineness are often used in jewellery.

Photomicrographs of typical silver-copper alloys are shown in *Figs.* 4, 7, 8, and 9 of the article on "Metals and Alloys, The Microstructure of."

§ (9) Lead-tin Series.—The alloys of lead and tin are of practical interest, chiefly from the point of view that they give rise to the soft solders. The most important of these are tinman's solder and plumber's solder. The first is made up in eutectic proportions (approximately 37 per cent Pb), while the latter contains two parts of lead to one of tin, and has a long crystallisation interval, which is made use of in forming "wiped joints."

The constitution of the system has been studied very thoroughly by Rosenhain and Tucker [4] and also by Degens.[5] The diagram given in *Fig.* 12 is taken mainly from the work of the former authors.

It will be seen that, as far as the liquidus is concerned, the alloys form a simple eutectiferous series, the eutectic temperature (182·5° C.) and composition (Pb 37·08 per cent) having been determined with great care by Rosenhain and Tucker. At 161° C. the well-known allotropic change in tin from the rhombic to the tetragonal system takes place. This is not indicated on thermal curves or by microscopic examination, but its existence has been shown by Degenes by dilatation measurements. At 149° C. a further reaction takes place, which is accompanied by a considerable evolution of heat, and by the rejection of tin from the solid solution. The

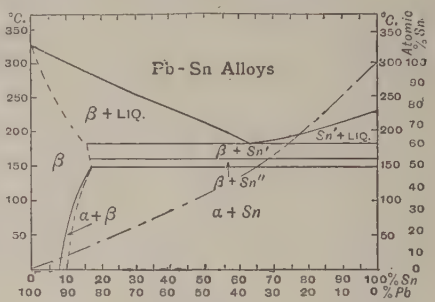


Fig. 12.

only possible explanation of this reaction appears to be that given by Rosenhain and Tucker, that the lead changes from a β allotrope into an α one. This change appears to take place at very low temperatures in pure lead (it has not yet been observed in this metal), but the addition of tin raises the transition temperature, which takes place along the 149° C. isothermal as soon as the lead is completely saturated with tin. The transformation is accompanied, on cooling, by the rejection of tin from the solid solution.

§ (10) Copper-manganese Series. — Manganese added to copper increases its tensile strength, particularly at high temperatures, and this fact has been made use of in the employment of copper containing about 5 per cent Mn for locomotive firebox stays. Apart from this use, the best-known copper-manganese alloy is manganin, though this is really

[1] *Phil. Trans. Roy. Soc.*, 1897, clxxxix. 25.
[2] *Metallurgie*, 1907, iv. 293.
[3] *Metallography*, p. 57.
[4] *Roy. Soc. Phil. Trans.*, 1909, ccix. 89.
[5] *Zeits. f. anorg. Chem.*, 1909, lxiii. 207.

a quaternary alloy of copper, maganese, nickel, and iron; but the proportion of the two latter elements is small. This metal, which has a high electrical resistance, and a very low temperature coefficient, contains about 82 per cent Cu and 15 per cent Mn, and is used for the manufacture of electrical resistance wires.

The constitution has been investigated by Schemtschuschny, Urazoff, and Rykowkoff,[1] and by Wologdine.[2] The diagram given in *Fig.* 13 is that obtained by the former workers. Wologdine obtained a very different diagram, but it appears probable that his alloys were contaminated with carbon.[3]

It will be seen that the component metals are completely soluble in each other, both in the solid and the liquid state, but that, unlike the copper-nickel series, the solidus and the

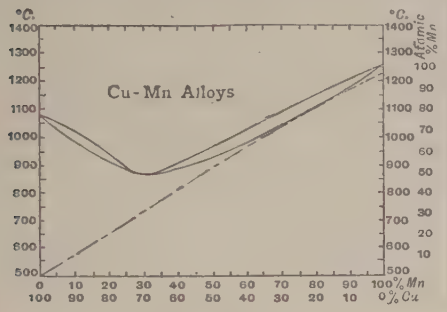


FIG. 13.

liquidus meet each other at a point intermediate between the two components.

§ (11) ANTIMONY-TIN SERIES. — The antimony-tin alloys are rarely used by themselves, but form the basis of bearing metals, and of Britannia metal. The former contains about 87 per cent Sn, 9 per cent Sb, and 4 per cent Cu, though alloys containing as much as 20 per cent Sb have been used. Britannia metal contains rather more tin and antimony, and somewhat less copper.

The constitution of the series is complicated, and, owing to the low temperatures at which many of the reactions occur, and the great tendency to metastability, the diagram (*Fig.* 14) is still incomplete. Further, the exact meaning of some of the lines on the diagram is uncertain.

The system has been investigated by Stead,[4] Reinders,[5] Gallagher,[6] and Williams,[7] and the diagram given in *Fig.* 14 is slightly modified from a combination by Gulliver[8] of the data obtained by these workers, who, it may be remarked, differ considerably *inter se.*

There are four primary separations from the liquid, the phases α, β, γ, and δ. It has been

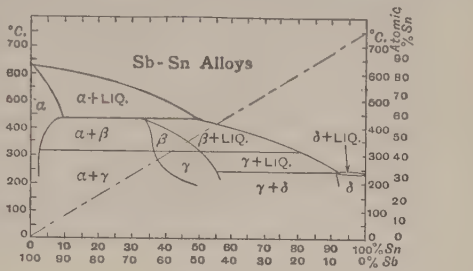


FIG. 14.

stated that β is a solution of a compound—of unknown composition—which is formed as a result of a reaction between α and the liquid. The β undergoes a transformation at about 315° C. when it is saturated with α, and 320° C. when it contains no α in solution. The exact cause of this transformation—whether it is a polymorphic change in the β or a reaction—is uncertain. The two bodies (β and γ) are indistinguishable microscopically from each other.

Finally, at 243° C. a further reaction

$$\gamma + \text{liquid} = \delta$$

takes place, and when less than about 8 per cent Sb is present δ separates from the liquid as a primary constituent.

§ (12) TIN-PHOSPHORUS SERIES.—Tin-phosphorus alloys are used in the manufacture of phosphor-bronze and certain other phosphoric alloys. The most important work on the constitution is that of Vivian,[9] who investigated the series between 0 per cent and 50 per cent P. His diagram, of which the one reproduced in *Fig.* 15 is a slight modification, is of extreme interest, as the tin-phosphorus system is the only metallic one whose examination has been carried so far that it cannot be regarded, practically, as a condensed system, *i.e.* one in which the vapour phase plays no part. It appears that, in this series, about 2·5 per cent P is the maximum amount which will exist in

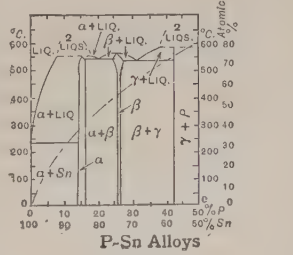


FIG. 15.

[1] *Zeits. f. anorg. Chem.*, 1908, lvii. 253.
[2] *Revue de Métallurgie*, 1907, iv. 25.
[3] Desch, *Metallography*, p. 52.
[4] *Journ. Soc. Chem. Indus.*, 1897, xvi. 200.
[5] *Zeits. f. anorg. Chem.*, 1900, xxv. 113.
[6] *Journ. Phys. Chem.*, 1906, x. 193.
[7] *Zeits. f. anorg. Chem.*, 1907, lv. 12.
[8] *Metallic Alloys*, p. 125.
[9] *Inst. of Metals J.*, 1920, xxiii. 325.

equilibrium with tin in the absence of the vapour phase; while with a vapour pressure of 1 atmosphere, 7 per cent P is the maximum content at the melting-point. In the work under consideration, the alloys were prepared in closed tubes, and were therefore under various pressures. As, however, the pressure has not a very great effect on the liquid and solid phases, it is probably not very far from the truth to consider that the diagram represents the system in equilibrium under a constant pressure equal to the maximum pressure actually attained.

The system is also interesting from other points of view. It contains three compounds (up to 50 per cent P), Sn_1P_3, Sn_3P_4, and SnP_3. Of these, Sn_3P_4, the basis of the β phase, is the only one which separates from the liquid at a maximum on the liquidus. The other two compounds dissociate at high temperatures into two immiscible liquids. The eutectic point of the first compound with tin is exceedingly near pure tin, and its melting-point is indistinguishable (under the conditions of the experiments carried out in the determination of the diagram) from the melting-point of tin. The compounds Sn_4P_3 and Sn_3P_4 form small ranges of solid solutions, while SnP_3 appears to have practically no solubility for the neighbouring phases.

§ (13) Copper-phosphorus Series.—Alloys of copper and phosphorus can be prepared up to 15 per cent P at atmospheric pressure, and the diagram has not been investigated above this composition. The compound Cu_3P is formed by separation from the liquid, and it gives rise to an eutectic containing 8·2 per cent P. The solid solubility has not been determined, but appears to be very small. The eutectic temperature is 707° C. and the melting-point of the compound is 1020° C., the copper content being 14 per cent. The equilibrium diagram is shown in *Fig.* 16.[1]

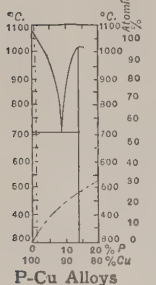


Fig. 16.

§ (14) Tin-zinc Series.— The tin-zinc series was investigated by Rudberg[2] in 1830, and also by Lorenz and Plumbridge,[3] Mazzotto,[4] and others. The diagram of these alloys is given in *Fig.* 17. It shows the system as a simple eutectiferous one, having no solid solubility areas. The melting-point of the eutectic is given as 197° C.

[1] Heyn and Bauer, *Zeits. f. anorg. Chem.*, 1907, liii. 129.

[2] *Poggendorf Ann.*, 1830, xviii. 240.

[3] Lorenz and Plumbridge, *Zeit. f. anorg. Chem.*, 1913, lxxxiii. 228.

[4] Mazzotto, *Int. Zeits. für Metallographie*, 1913, iv. 273.

§ (15) Iron-nickel Series.— The iron-nickel series is of particular interest for two reasons. In the first place, it is one of the most persistently metastable systems known,

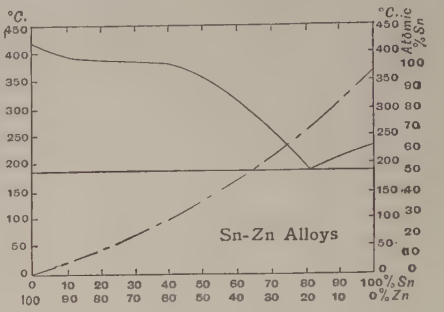


Fig. 17.

and secondly, the alloys form, with carbon, a very important series of ternary steels.[5]

The constitution has been studied by a very large number of workers, of whom the most important are referred to below,[6] but even yet it has not been found possible to fix completely the whole diagram, though that given in *Fig.* 18 is probably a close approach to the truth. The liquidus of this diagram is that obtained by Ruer, while the transformations in the solid are taken from Hanson and Hanson's paper. To illustrate the metastability of the system the dotted lines are introduced. The upper one of these indicates the temperature at which arrests are found on heating, and the two lower ones on cooling specimens, the observations being made by thermal analysis, by magnetic measurements, or by resistivity measurements. The broken lines indicate incompletely determined parts of the diagram. It will be seen that the alloys, when just solid, form a continuous series of solid solutions, the liquidus being very close to the solidus, and having a minimum at about 70 per cent Ni. This solid solution is known as γ, and is non-magnetic. At lower temperatures the γ undergoes a transformation, as a result of which the material becomes magnetic and the electrical resistivity falls. In pure iron this is the well-known A_3 point. The magnetic variety of nickel forms a long series of solid solutions known as δ. It appears as though δ were really the compound $FeNi_2$ containing iron or nickel in

[5] *Vide* article on "Steels, Some Special"; also "Invar."

[6] Osmond and Cartaud, *Rev. de Mét.*, 1904, viii. 69; Guertler and Tammann, *Zeits. für anorg. Chem.*, 1905, xlv. 205; Levin, *Zeits. für anorg. Chem.*, 1905, xlv. 283; Frankel and Tammann, *Zeits. für anorg. Chem.*, 1908; Ruer, *Metallurgie*, 1909, vi. 679; Benedicks, *Rev. de Métallurgie*, 1911, p. 85; Honda and Tagaki, *Science Reports, Tohoku Impl. Univ.*, 1917, vi. 321; Hanson and Hanson, *Iron and Steel Inst. J.*, 1920, cii. 39.

solution according to the composition. This δ forms an eutectoid with α.

Nickel has the effect of depressing both the A_3 and the A_2 points in iron.[1] The absolute shape of the diagram in this region requires further investigation.

The behaviour of some of the alloys under any but excessively slow changes of temperature is very interesting. Consider, for example, alloys containing 25 per cent and 35 per cent of nickel. If a sample of the former be cooled from below the solidus at a slow rate it will remain non-magnetic till a temperature of about 150° C. is reached, when it will become magnetic. On reheating, the metal will not lose its magnetism until it has been heated to about 580° C. A sample containing 35 per cent Ni behaves similarly, except that it requires to be cooled to about −100° C. before it becomes magnetic, and it loses its magnetism on heating at about 500° C. This great lag, which persists even when the heating or cooling lasts over many hours or even days, has given rise to a division of the iron-nickel series into reversible and irreversible alloys. In the former the lag between heating and cooling curves is small, in the latter it is large.

Iron-nickel alloys are of special interest, as they occur native, both on the earth and, in the form of siderites, as visitants from other worlds. In the latter case the iron content generally varies from 80 per cent to 95 per cent, the nickel ranging from 5 per cent to 10 per cent, but one meteorite has been found containing 60 per cent Ni. The best-known of the native terrestrial nickel-iron masses—that found at Ovifak in Greenland—contains 1 per cent to 2 per cent Ni, while grains containing as much as 75 per cent Ni have been found in the sands of the River Frazer in British Columbia.[2]

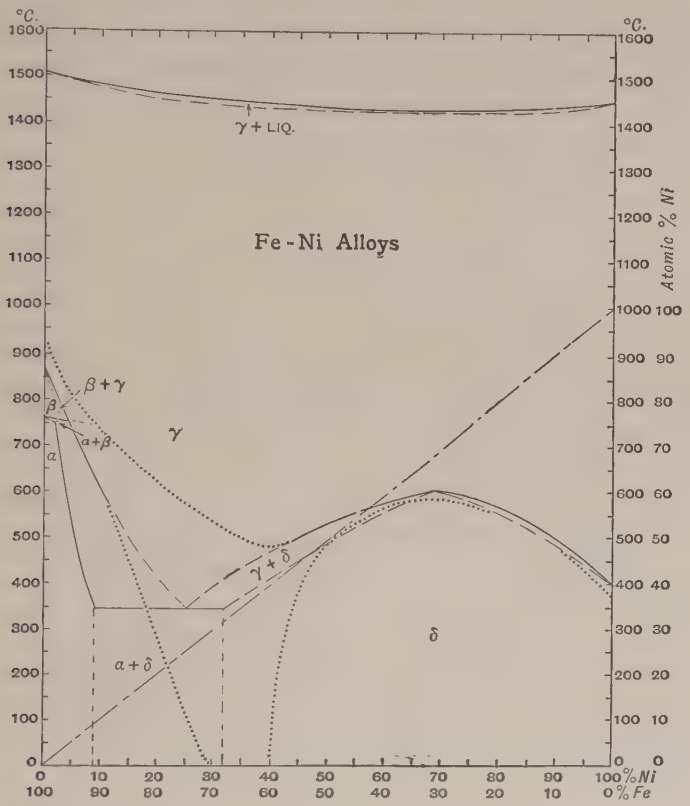


FIG. 18.

§ (16) IRON-MANGANESE SYSTEM. — As in the case of nickel, manganese is important as a constituent in steels, binary alloys of iron and

[1] *Vide* article on the "Iron-carbon Alloys."

[2] *Vide An Introduction to the Study of Meteorites*, L. Fletcher.

manganese not being used. Their constitution has been studied by Levin and Tammann,[1] and by Osmond.[2]

The system belongs to the simple type in which the metals are completely soluble in the liquid and in the just solid states. At lower temperatures the alloys undergo a magnetic transformation, the change in iron being lowered by the addition of manganese; but this point has received but little study, and the data are insufficient to justify the

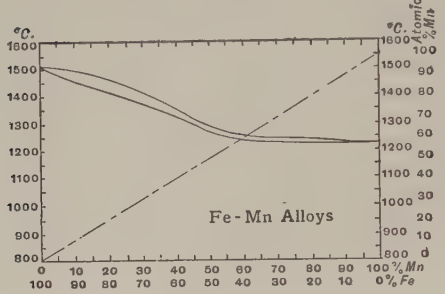


FIG. 19.

drawing of a line to indicate the transformation on the diagram which is given in *Fig.* 19.

II. TERNARY SYSTEMS

We have seen [3] that it is possible to represent the constitution of ternary systems in two dimensions by projecting the various surfaces, one set at a time, on to a triangular base, and drawing isothermal lines on to the projection. In this way it is possible to obtain in a very small number of diagrams a complete representation of a ternary system. In proceeding to discuss actual cases we are confronted with the fact that, up to the present, no ternary system has been completely investigated. As, however, a representation of an ideal complete system has already been given in the article on "Alloys, The Equilibrium Diagram," [4] the following more or less incomplete systems will be readily understood. Where sufficient data exist, the method of projecting planes on to a base and drawing isothermals on to them has been adopted. In one or two cases the actual position of these isothermals has not been determined, but their general trend is sufficiently obvious. In such cases they have been drawn, and the uncertainty noted in the text. Finally, there are examples in which the data given are too meagre for this, and the isothermals have been omitted.

[1] *Zeits. f. anorg. Chem.*, 1905, lvii. 136.
[2] *Rev. de Métallurgie*, 1905, ii. 595.
[3] "Alloys, The Equilibrium Diagram," § (4).
[4] *Ibid.* § (4).

§ (17) THE LEAD-TIN-BISMUTH SERIES.—This system is of interest as being the first ternary system whose liquidus was completely worked out. This was done by Charpy,[5] whose results are plotted in *Fig.* 20, with slight modifications introduced by Shepherd.[6] The contour lines on this, and the majority of the remaining figures, are drawn at intervals of 20° C. The areas of separation of the three primary constituents are seen sloping down towards the eutectic point.

The next diagram, *Fig.* 21, represents the second set of separations which take place on cooling the alloys. The planes here represent the commencement of separation of the depressed binary eutectics. The shape of the contour lines has not been determined, but the various solubility limits in the binary systems, as well as the composition and temperature of separation of the three binary eutectics and the ternary eutectic, are known, so that the principal uncertainty is introduced by the fact that the solubility limits in the ternary system are unknown. These undetermined factors also render uncertain the shape and position of the various lines of *Fig.* 22, which represents the solidus temperatures and compositions of the system.

A further diagram, representing the effect of bismuth and tin on the allotropic modification of lead, discovered by Rosenhain and Tucker,[7] and another showing the influence of lead and bismuth on the allotropic change in tin, are required to complete the diagram. No work, however, has been done on this subject.

§ (18) THE COPPER-NICKEL-ZINC SERIES.—This system contains alloys of considerable commercial value, the most important being those known under the name of nickel-silver or German silver. When used for table ware, these contain from 55 per cent to 60 per cent of copper, 20 per cent to 25 per cent of zinc, and about 20 per cent of nickel; for other purposes the nickel may range between 6 per cent and 35 per cent, while the zinc content varies between 15 per cent and 30 per cent. The large range in which these alloys exhibit useful properties is connected, as in binary systems, with the considerable extent of the α field, which, incidentally, is very large in the three binary systems from which the ternary series is built up.

The constitution of these alloys has been investigated by Tafel.[8] Except at the zinc-rich end, the liquidus surface (*Fig.* 23) has been reasonably well determined, and the same applies, though to a lesser extent, to the solidus surface (*Fig.* 24). Reactions between the

[5] *The Metallographist*, 1899, ii. 26.
[6] *Journ. of Physical Chemistry*, 1902, vi. 519.
[7] See above, § (9).
[8] *Metallurgie*, 1908, v. 343.

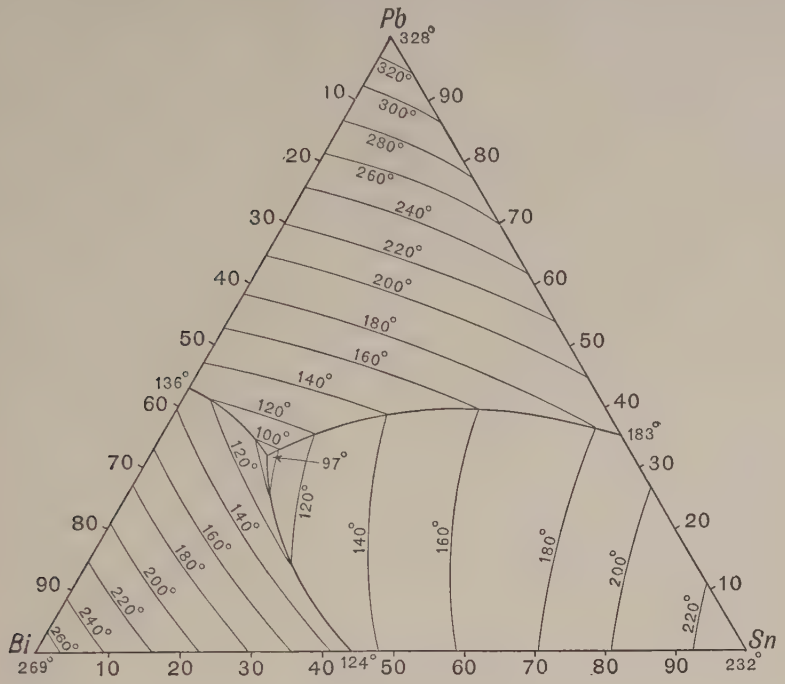

Pb
328°
320°
300°
280°
260°
240°
220°
200°
180°
160°
140°
120°
100°
97°
136°
183°
Bi
269°
124°
232°
Sn

FIG. 20.

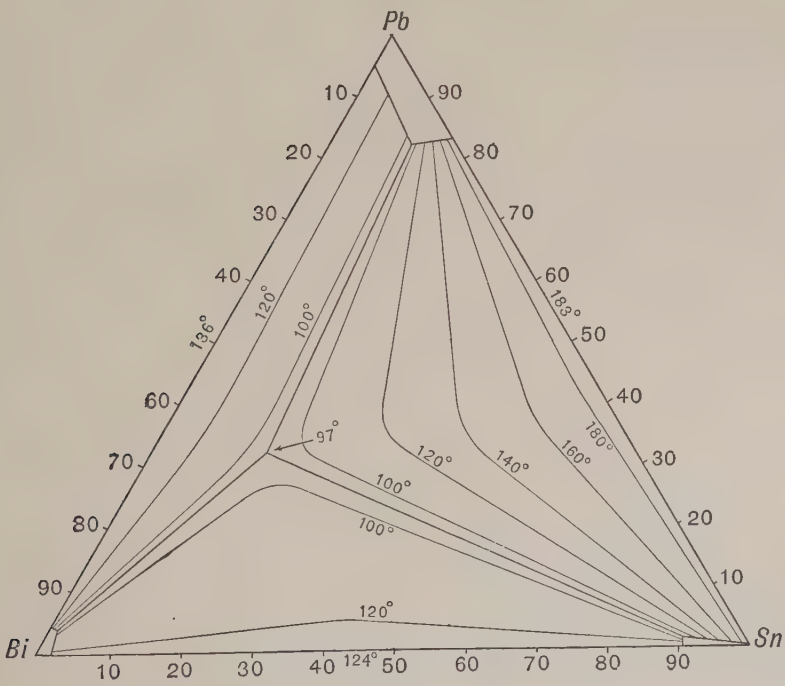

Pb
136°
120°
100°
97°
183°
120°
140°
160°
180°
200°
220°
240°
260°
Bi
124°
Sn

FIG. 21.

liquidus and the solidus only occur in alloys rich in zinc, and, for the greater part, these have not been determined, except over small ranges. It has not, therefore, been considered advisable to draw a contour diagram representing them.

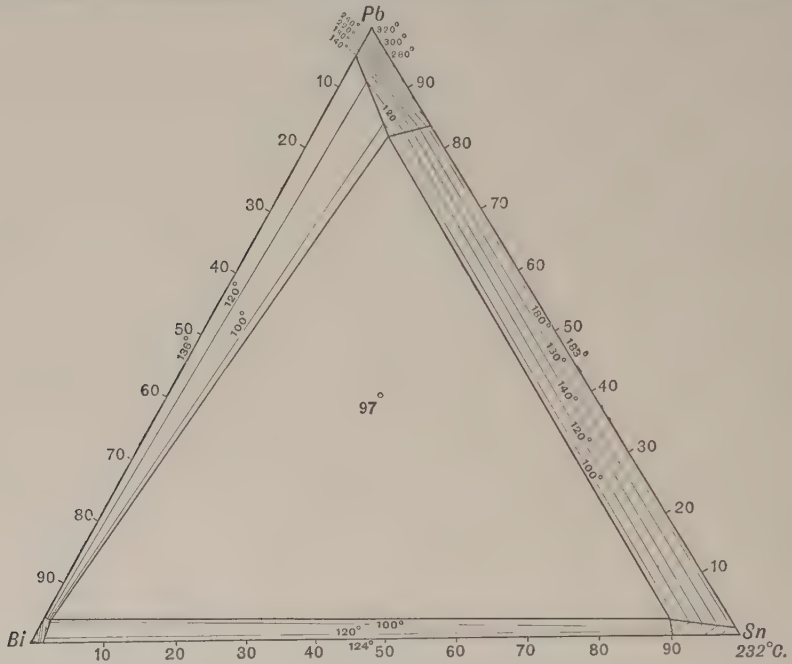


FIG. 22.

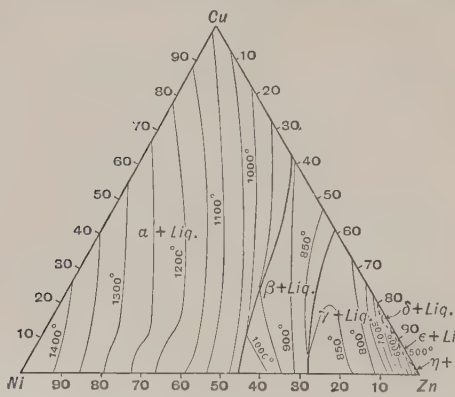


FIG. 23.

It may be noted that sections through a model representing equilibrium conditions, and parallel to the copper-nickel side of the composition triangle, are almost replicas of the copper-nickel diagram (moved down with respect to the temperature ordinate) so long as they do not contain more than about 40 per cent of zinc; while sections parallel to the nickel-zinc side resemble, in the same way, the nickel-zinc diagram when not more than about 40 per cent of copper is present.

Practically all the alloys of commercial

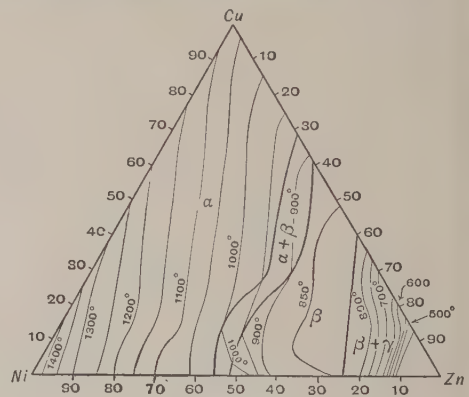


FIG. 24.

importance lie in the α range. While the most important of these are the nickel-silvers referred to above, mention may be made of casting alloys containing approximately 70 per cent of copper, 20 per cent of nickel, and 10 per cent of zinc, and of an alloy with a high electrical

resistance, sold under the name of platinoid, which contains about 60 per cent of copper, 14 per cent of nickel, 24 per cent of zinc, and some tungsten.

§ (19) THE COPPER-ZINC-TIN SERIES.—Excepting the pure copper-zinc alloys, brass and Muntz metal, copper-zinc-tin alloys are much more used than any other non-ferrous alloys. In spite of this the equilibrium diagram of the ternary system is only partially known, even in the region where the alloys are of commercial value. This is doubtless due, in measure, to the complications in the component binary systems, which, as we have seen above, are by no means completely determined.

The following list gives the composition of a few of these alloys:

Alloy.	Cu.	Zn.	Sn.
Coinage bronze . . .	95	1	4
Admiralty gun-metal .	88	2	10
Bearing bronze . . .	80-88	2-5	8-15
Locomotive whistles .	80	2	18
Admiralty condenser tubes	70	29	1
Naval brass	62	37	1
Special Admiralty anti-friction alloy . . .	1·5	29·5	69

The constitution of the series has been studied, principally by Hoyt [1] and by Hudson and Jones.[2] *Fig.* 25 shows the liquidus surface, as far as it has been determined by Hoyt, *i.e.* up to about 50 per cent of zinc and

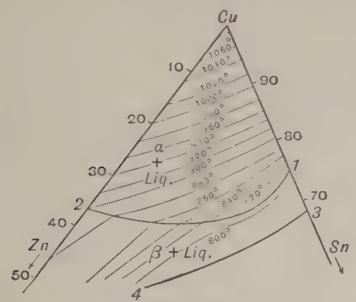


FIG. 25.

30 per cent of tin. This part of the diagram is simple; α separates over the area Cu-1-2, the slope of the surface being greater near the copper-tin side of the area than near the copper-zinc side. In the area bounded by the lines 2-1, 1-3, and 3-4, and extending beyond the field investigated in alloys containing much zinc, β separates from the liquid. Beyond this the system has not been studied.

No data have been published from which it is possible to construct a diagram representing the reactions occurring between the liquidus and the solidus, but *Fig.* 26 gives the solidus

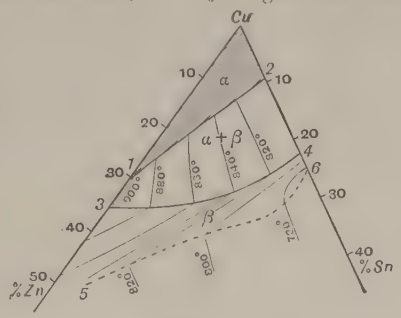


FIG. 26.

surfaces of the copper-rich end of the system. This figure is constructed, as far as the various boundaries of the phase fields are concerned, from Hoyt's data, the dotted line being put in by him on theoretical reasoning only. The actual slope of the surfaces has not been determined in the ternary system, but the slopes of the binary system lines are known, and points of equal temperature on the edges of the triangle have been joined by more or less straight lines. It follows, therefore, that the isothermals are only of value in suggesting the general slope of the surfaces, and are not to be regarded as accurate.

The area Cu-1-2 represents the field in which final solidification takes place by the separation of α. The next part of the solidus is the peritectic area 1-2-4-3. Here we have the reaction

$$\alpha + \text{liq.} = \beta.$$

Then in the area 3-4-6-5 the alloys solidify completely as β, while beyond that the reaction

$$\beta + \text{liq.} = \gamma$$

takes place.

Fig. 27 shows the contour lines and area connecting up the eutectoid in the copper-tin

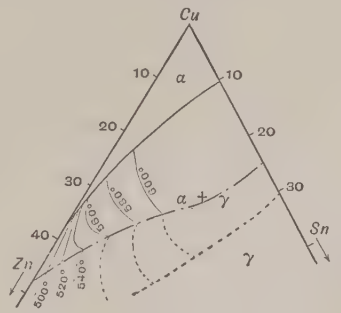


FIG. 27.

series with the line at 490° C. in the copper-zinc series.

[1] *Inst. of Metals J.*, 1913, x. 235; and 1915, xiv. 178.

[2] *Ibid.*, 1915, xiv. 98.

Finally, *Fig.* 28 shows Hudson and Jones' diagram for the constitution, when solid, of alloys containing between 50 per cent and 70 per cent of copper and between 0 per cent and 5 per cent of tin. This is reproduced on a larger scale than the other diagrams, as it is somewhat complicated and contains the most important of the brasses. It will be seen that the area is divided into six groups, of which two are single-phase areas, three are two-phase areas, and one is a three-phase area. The diagram is self-explanatory.

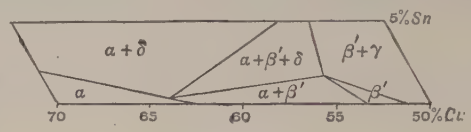


FIG. 28.

§ (20) THE COPPER-ALUMINIUM-TIN SERIES.—The alloys of copper, aluminium, and tin have been investigated by Edwards and Andrew.[1] It appears that but a very small proportion of the alloys are likely to be of any practical value, but theoretically the whole diagram is of very great interest, and the liquidus surface has been worked out with, probably, more completeness than any other ternary system. It is reproduced in *Fig.* 29. It will be seen that neither ternary eutectics nor ternary compounds are formed. Certain points, however, call for consideration. The first of these is the curious ridge running from pure copper downwards. Edwards and Andrew state that the constituents separating on either side of this ridge are the copper-tin α solution, probably containing some aluminium in solution, and the copper-aluminium α solid solution, possibly containing a certain amount of tin in the same way. Other evidence in the paper appears to indicate that these two components are isomorphous, and should therefore form a single phase. The sharp change in the contours is very marked, however, and strongly suggests that some boundary-line such as that drawn by the authors is required. Generally speaking, it is not clear from the diagram what are the

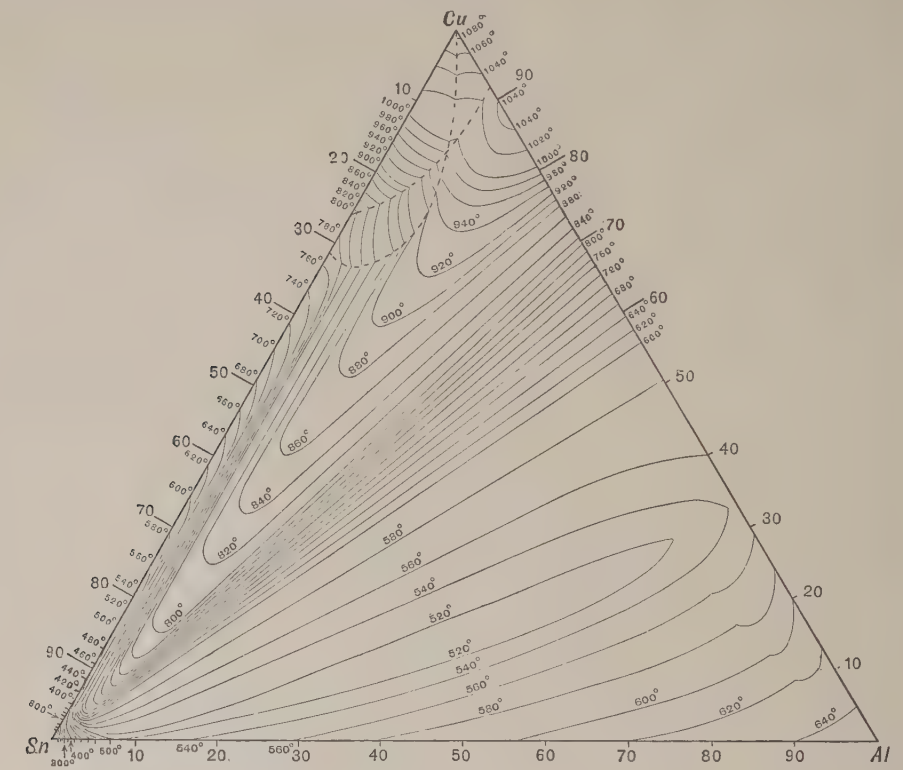


FIG. 29.

[1] *Royal Soc. Proc.*, 1909, lxxxii. 568; *Inst. of Metals J.*, 1909, ii. 29.

phases separating from the liquid, and they have therefore not been inserted.

In the tin-rich part of the diagram the contours lie so close together that it has not been possible to draw them all. The starting-points on the sides of the triangle are, however, marked in all places.

Fig. 30 shows the constitution of the alloys at ordinary temperatures. Diagrams of intermediate separations are not shown, because the authors have not indicated any of the temperatures at which the reactions take place, which renders it impossible to draw the contour lines.

Fig. 30 is self-explanatory, but calls for one or two comments. One of these is the large area in which the compound $CuAl_2$ appears. It will be noticed that it occurs over at least two-thirds of the diagram, and exists very

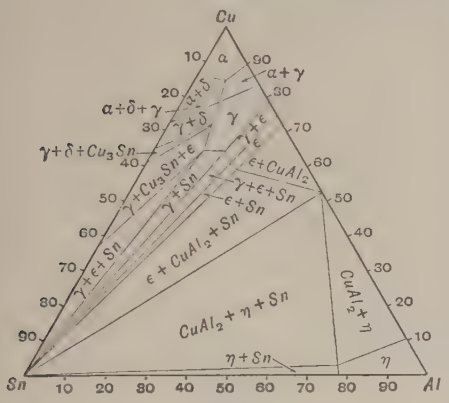


FIG. 30.

nearly down to the pure-tin corner. The same is true of pure, or almost pure, tin. Of the remaining constituents, δ and ϵ are probably compounds (Cu_4Sn and CuSn), while Cu_3Sn obviously is one. Remembering that compounds are hard, brittle phases, it is not surprising that the range of useful alloys is small in this series. It is also worth drawing attention to the curious fact that two fields containing $\gamma+\epsilon+Sn$ are shown in the figure. The meaning of this is very obscure.

§ (21) THE COPPER-ALUMINIUM-ZINC SERIES. —Copper-aluminium-zinc alloys rich in copper are chiefly used in naval work, on account of the fact that they are supposed to resist corrosion better than brasses. It is certainly true that the copper-aluminium alloys are better in this respect than those consisting of copper and zinc. The maximum strength and the elastic limit are also considerably raised by the addition of aluminium to copper-zinc alloys, the composition used being generally about

Cu . . .	65 to 70 per cent.
Zn . . .	27 to 33 per cent.
Al . . .	1 to 4 per cent.

Such alloys may have a tensile strength up to 35 kilos per sq. mm. with an elongation of 50 per cent on 25 mm.

The constitution of the series is far from being completely studied. At the copper-rich end Carpenter and Edwards [1] have investigated the liquidus surface of the system up to 50 per cent of added metals, while at the zinc corner Haughton and Bingham [2] have investigated the liquidus for alloys containing not more than 10 per cent of copper and 15 per cent of zinc. The former workers have also studied the constitution (down to 400° C.) of alloys containing up to 50 per cent of zinc and 15 per cent of aluminium, while the latter investigators have given diagrams representing the constitution (down to 200° C.) of the series whose liquidus surface they worked out.

The liquidus contours are shown in *Fig.* 31. Considering the copper-rich alloys first, the much greater influence of aluminium, compared with zinc, is seen by the shape of the area CuAB, over which α is the primary separation.

The next area, ABCD, is the *locus* of separation of β. In the copper-aluminium series the liquidus has a pronounced maximum at this point, and it will be seen that this maximum persists well into the ternary system, only dying out quite near the copper-zinc side of the triangle. In the area CDFE, γ is the primary separation, but the exact position of the line FE has not been determined. The same applies to the lines GH and KL, which are the boundaries between the areas where δ, ϵ, and $CuAl_2$ are the primary separations. From the shape of the contour lines it would appear as though there was a ternary eutectic in the neighbourhood of the point M. Another ternary eutectic appears at the point Q, and has a composition of Cu 4 per cent, Al 7 per cent, Zn 89 per cent, its melting-point being 378° C. In the area ZnNQP, η, a zinc-rich solid solution, is the primary separation, while Al_2Zn_3 crystallises out from the liquid in the area to the right of PQO, and ϵ (a copper-zinc solid solution) to the left.

As stated above, Carpenter and Edwards made a very complete study of the reactions taking place below the liquidus for alloys lying in the area CuCD (*Fig.* 32), and from the results they constructed a model representing the constitution of the series. This was formed in plaster, and each phase space was made detachable, so that the model could be "unbuilt" to reveal the various reactions. Photographs illustrating this unbuilding are given in the paper, and while they serve admirably to illustrate the various phase relationships occurring in the series, it is

[1] *Internat. Zeits. für Metallographie*, 1912, ii. 209.
[2] *Roy. Soc. Proc.*, 1921, xcix. 47.

not possible to obtain from them data for the construction of projected sections of the model. The reader must, therefore, be referred to the original paper for further information on this part of the diagram.

The investigators of the zinc corner of the diagram have reproduced a large number of sections through the diagram perpendicular to the base, and from these it has been possible to construct the projections given in *Figs.* 32 and 33. The first of these represents the reactions occurring between the liquidus and the solidus. The area UVQT represents the commencement of separation of the depressed binary eutectic of the aluminium-zinc series. As this surface only falls 2° C., no isothermal contours are shown on it. Over the area NQS

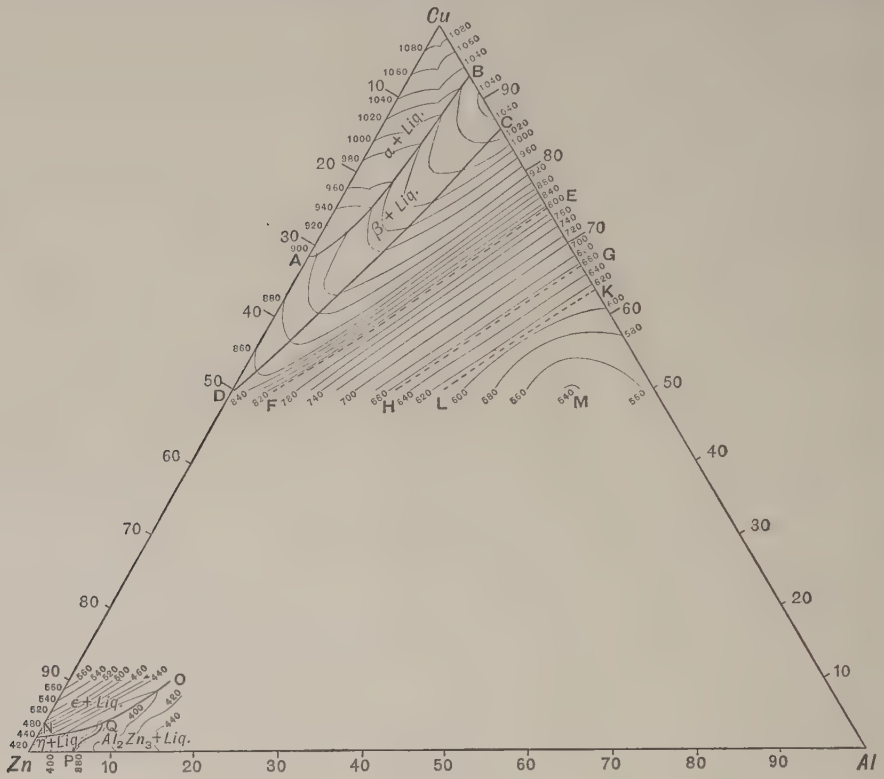


FIG. 31.

η is deposited as the result of the commencement of the reaction ϵ + liquid = η, while in the area SQT $\beta + \epsilon$ commence to separate together. Finally, the very steeply sloping area NQR represents the boundary between the $\eta + \beta$ + liquid and the $\eta + \epsilon$ + liquid fields.

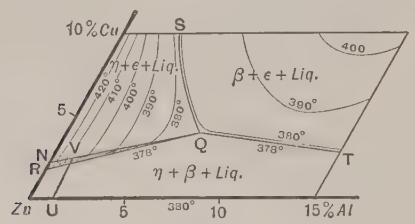


FIG. 32.

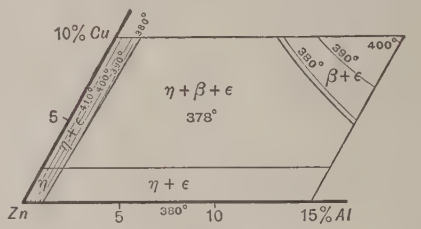


FIG. 33.

Fig. 33, which represents the solidus surfaces, is self-explanatory.

To complete this part of the diagram a section showing the reaction $\beta = \eta + \gamma$ should be shown. As, however, this appears to

occur in all the alloys in this area containing over 1 per cent of aluminium, at a constant temperature of 280° C., it is not necessary to reproduce such a section here.

§ (22) THE COPPER-ALUMINIUM-MAGNESIUM SERIES.—The constitution of alloys of aluminium containing up to somewhat over 50 per cent of copper and of magnesium has been carefully studied by Vogel.[1] The series is interesting, amongst other reasons, in that it shows very definitely the existence of the ternary compound Al_6Mg_4Cu. The binary systems contain the two compounds $CuAl_2$ and Al_3Mg_4,[2] and the diagram given may be considered to be a complete representation of the system $Al - Al_3Mg_4 - CuAl_2$ instead of a partial one of the system Al – Mg – Cu. The author has reproduced his results mainly in

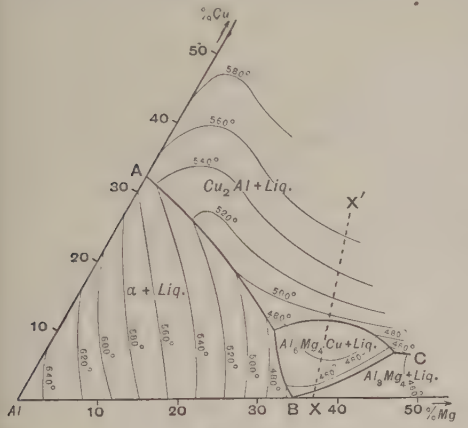


FIG. 34.

the form of seven sections perpendicular to the base of the equilibrium prism, but at various angles to the sides. The way these sections are chosen leaves certain fairly considerable areas of the composition triangle having no sections passing through them, and this has rendered difficult the drawing of contour lines; indeed in some cases the position of these lines is largely a matter of assumption, though it is thought that, as a general outline, the diagram is not very wrong; appreciable errors may, however, have been introduced by the fact that the aluminium used contained 1·2 per cent of iron and slightly more silicon.

Fig. 34 represents the liquidus surfaces of the alloys. It consists of four areas: (1) That in which the aluminium-rich solid solution α separates from the liquid; (2) the field in which $CuAl_2$ is the primary separation (only a part of this and the next field lies in the area under discussion); (3) the area in which the compound Al_3Mg_4 is the first material to crystallise; and (4) the curious, more or less mound-shaped area which represents the *locus* of existence of the ternary compound Al_6Mg_4Cu as a primary separation. This latter is specially interesting, as the alloy whose composition is that of the compound does not lie in the area at all. This is only possible because the area in question does not contain a maximum on the liquidus curve of *every* section drawn through it. A section through the line XX′ (*Fig.* 34), *i.e.* one passing through the composition of the compound[3] and the area where it is a primary separation, would have a liquidus something like that shown in *Fig.* 35, that is to say, the compound, on heating, dissociates at a temperature lower than that of the liquidus, and the section is similar to the "hidden maximum" type occurring in binary systems.[4]

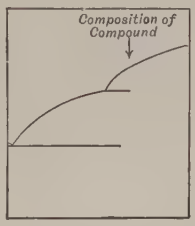


FIG. 35.

The secondary separations are shown in *Fig.* 36, and the solidus surfaces in *Fig.* 37.

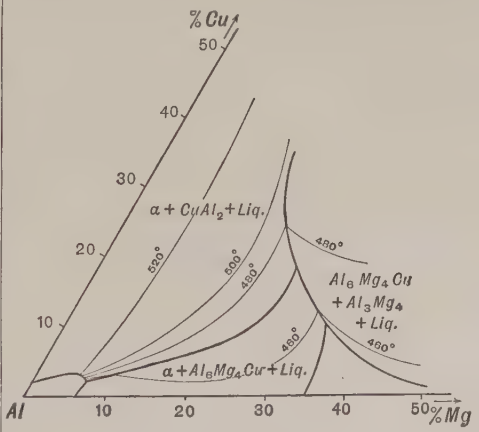


FIG. 36.

In a small region in the neighbourhood of the ternary compound, a further diagram would be needed to complete the system, as there are two reactions between the liquidus and the solidus. As, however, these occur over a small

[1] *Zeits. für anorgan. Chemie*, 1919, cvii. 265.

[2] This investigation was carried out before the work of Hanson and Gayler called in question the existence of the compound Al_3Mg_4 (see § (7) above). The diagram given is that of Vogel, as the existence or otherwise of this compound would not appreciably affect the main part of the diagram.

[3] The composition of the compound is: Cu, 19·5 per cent; Al, 50·5 per cent; Mg, 30 per cent.

[4] See article on "Alloys, The Equilibrium Diagram," §§ (3), (6).

area only, and as they have not been completely studied, this extra section has been omitted.

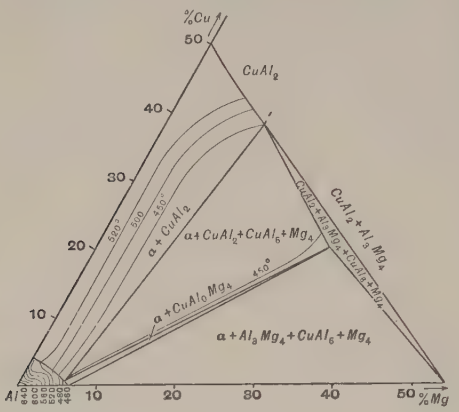


FIG. 37.

§ (23) THE COPPER-ALUMINIUM-MANGANESE SERIES.—The copper-rich alloys in this series containing up to 11 per cent of aluminium and 10 per cent of manganese, and the aluminium-rich alloys, containing not more than 4 per cent of either copper or manganese, have been very thoroughly studied from the point of view of their mechanical properties by Rosenhain and Lantsberry.[1] Certain alloys in the former group possess some very valuable properties. For example, a material consisting of 89 per cent of copper, 10 per cent of aluminium, and 1 per cent of manganese has the following mechanical properties :

Condition.	Elastic Limit. kg./sq. mm.	Maximum Stress. kg./sq. mm.	Elongation. Per cent.
Sand cast .	..	36	22
Chill cast .	..	40	25
Hot rolled.	8	42	30

The study of the constitution of these alloys has not been carried as far as the study of their mechanical properties. The authors above mentioned have determined the liquidus surface of the copper-rich alloys with great care, and have taken a large number of cooling curves, but they state that " the data available, although very numerous, are not adequate for the solution of the very complex problems involved. . . . The conclusions arrived at are, briefly, that, within the limits of the alloys studied, the constitution of the ternary alloys very closely resembles that of the binary alloys of copper and aluminium. . . . In no case does manganese give rise to the formation of a third phase, so that all the alloys consist of either a single solid solution (the α body), or of two phases, in each of which manganese exists in the form of a solid solution. The compound Cu_9Al appears to be capable of dissolving manganese, and there is no evidence of the formation of a ternary compound."

The liquidus surface is shown in *Fig.* 38.

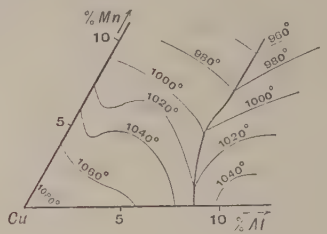


FIG. 38.

With reference to the constitution of the aluminium-rich alloys, the authors give no diagram, but state that " the alloys all show at least two definite arrest points, while the majority show three, and two even show four, such points. . . . In these alloys three distinct phases are found. These are a solid solution which is pure, or nearly pure, aluminium, containing some copper but practically no manganese in solid solution, the aluminium-copper compound $CuAl_2$, and the aluminium-manganese compound Al_3Mn. . . . A ternary eutectic of the three phases is probably found in most of these alloys."

§ (24) THE ALUMINIUM-MAGNESIUM-SILICON SERIES.—As all these elements are very light (aluminium being the heaviest) they appear to form a hopeful series for the manufacture of light alloys. Up to the present, however, not much work has been done on them from this point of view. Nor has the constitution yet received much attention, with the exception of the aluminium corner, where alloys containing up to 35 per cent of magnesium and 12

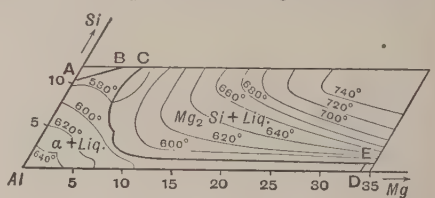


FIG. 39.

per cent of silicon have been examined by Hanson and Gayler.[2]

Fig. 39 represents the liquidus surface for the series. In the area AlABCED the aluminium-rich solid solution crystallises out

[1] Ninth Report to the Alloys Research Committee.

[2] *Inst. of Metals J.*, 1921, xxvi. 321.

from the liquid. Beyond DE the primary separation is the compound Al_3Mg_2, but this hardly enters the part of the diagram under consideration. The area beyond AB, of which, again, only a very small part enters into the present discussion, is the *locus* of separation of nearly pure silicon. Over the greater part of the diagram the primary crystallisation consists of the compound Mg_2Si. This is an interesting and somewhat unusual case [1] of a compound in one of the binary systems reaching very far towards the corner of the third metal, *i.e.* the one which does not enter into the composition of the compound.

The fields of the secondary separation are shown in *Fig.* 40, which is divided into four

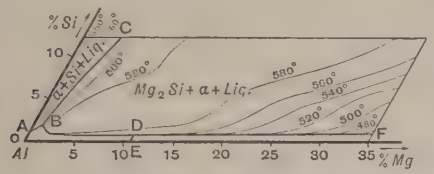


FIG. 40.

areas. In the two areas AlABDE and MgEDF there is no separation between the liquidus and the solidus. Below the area SiABC the constituents are $\alpha+\beta+$liquid, while the convex area occupying the rest of the diagram is the upper surface of the space consisting of $\alpha+Mg_2Si+$liquid.

Fig. 41 shows the solidus surfaces. Below

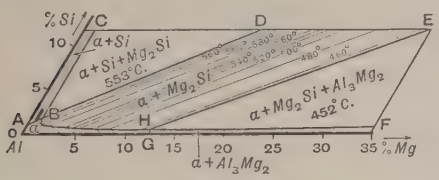


FIG. 41.

the area AlABHG, α alone exists, while the steeply sloping area SiABC is the surface below which $\alpha+\beta$ exists. The triangular space CBD is the horizontal "binary eutectic" of β and Mg_2Si, so that the phases existing below this are $\alpha+\beta+Mg_2Si$. In the next area DBHE the surface rises sharply from DB and then falls to HE. Below this the phases are $\alpha+Mg_2Si$. With the addition of more magnesium, we arrive at the horizontal surface EHF, which may be regarded as the "binary eutectic" of Mg_2Si and Al_3Mg_2; these two phases, together with α, form the constituents existing below this plane.

[1] Compare the compound $CuAl_2$ in the copper-aluminium-tin series, § (20) above.

Finally, there remains the narrow area FHGMg, which represents the binary eutectic of aluminium and Al_3Mg_2, and is practically horizontal.

J. L. H.

ALLOY "Y": an alloy of aluminium containing 4 per cent of copper, 2 per cent of nickel, and 1·5 per cent of magnesium. See "Aluminium Alloys," § (9).

ALLOYS, THE EQUILIBRIUM DIAGRAM

THE constitution of a series of alloys can be represented by means of the equilibrium diagram. In other words, it is possible to show on such a diagram the phases which exist in any alloy of the series at any given temperature, and further, the relative amounts of the phases which occur when the alloy is in equilibrium can be deduced from the diagram.

Restricting ourselves, for the sake of simplicity, to the consideration of systems which contain only two components, we can plot, on a rectangular co-ordinate diagram having temperatures as ordinates and compositions as abscissae, lines dividing the area into a number of fields each of which represents the region in which definite phases, indicated by the microscope or by thermal analysis, occur. Such a diagram as is shown in *Fig.* 1 represents one of the simplest cases which are found. Here M and N represent the two component metals, and the line MN is divided in such a way that the ordinate from any point F represents an alloy containing M and N in the ratio M : N :: NF : FM. The distance of any point on such an ordinate above the line MN represents a temperature. The various lines AB, AD, etc., denote the temperatures and compositions at which various phase changes occur in the alloys. To the more important

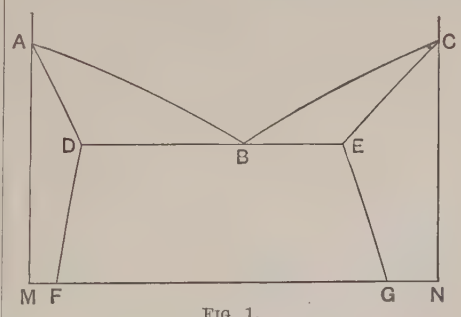


FIG. 1.

of these lines names have been given. Above ABC the alloys are completely liquid, and ABC is known as the *liquidus*. The lines AD, DE, and EC make up the *solidus*, below which all the alloys are completely solid. The liquidus and the solidus meet, in the case

under consideration, at the points A and C, which are the melting points of the pure metals, and B, which is known as the *eutectic point.* (They can also meet at other points—see § (3) below.) The eutectic alloy is defined as one which lies at a minimum on the liquidus, has a constant freezing and melting point, and is formed of two separate phases (in binary systems). In many cases, as will be seen later, such alloys are of considerable importance.

The lines DF and EG are the limits of solid solubility of the component metals in each other.

§ (1) The Phase Rule.—The equilibrium diagram is so called because it represents the condition of the alloys when in a state of equilibrium. This term[1] will be discussed later. It is often known as a constitutional diagram, for obvious reasons, and also as a phase diagram. It owes this name to the fact that it is based on the phase rule of Willard Gibbs. This very important law was deduced from thermodynamic considerations in 1874 to 1878, and about ten years later it was re-stated in less mathematical language by Roozeboom. The mathematical foundations of the law cannot be discussed here; it is generally stated in the form of the equation

$$f = c + 2 - p,$$

where f is the number of degrees of freedom of the system, p the number of phases present, and c the number of components in the system. For a full discussion of these terms reference must be made to a treatise on the phase rule, a brief description only being given here.

(i.) *Components.* — The components of a system are those materials from which the system is built up. In the case of alloys, they may in general be taken as the pure metals forming the system, though where a compound $MxNy$ of two metals M and N is formed the alloys may be divided into two systems, of which the components are the metal M and the compound in one case, and the metal N and the compound in the other case.

(ii.) *Phases.*—A phase is a homogeneous portion of the system which is physically separable from the adjacent portions. For example, in the case of solid crystals coexisting with a liquid, the crystals are one phase and the liquid is another.

(iii.) *Degrees of Freedom.*—By degrees of freedom is meant the number of factors (temperature, pressure, and concentration) which must be *arbitrarily* fixed in order that the condition of the system may be completely specified. For example, if it is necessary to fix or specify two of the three factors, temperature, pressure, and concentration,[2] of a system before we know the conditions under which that system exists, *i.e.* before we know the value of all these factors, then the system is said to have two degrees of freedom. Or to put it in another way. Suppose we can vary two of these factors *independently* without altering the system, we are dealing with two degrees of freedom. Any gas constitutes such a system; for, to know all the conditions under which that gas exists, we must specify two of them, *e.g.* for every temperature and pressure the gas can have only one concentration. Conversely, we can alter two of these factors *independently* without causing the gas to change its state.

(iv.) *Application of the Rule.*—Now suppose the gas to be cooled down, without dissociating, to such a temperature that it commences to liquefy, we have then two phases present. In this case it is only necessary to specify one of the factors and the whole system is defined. If we fix on any temperature, the pressure at which the gas and liquid coexist is automatically fixed, and the concentration is also fixed. Alteration of any one of the factors means that both other factors must be altered. Such a system is said to possess one degree of freedom.

Finally, let us imagine that the material is cooled down still further, until the solid commences to separate. There are then three phases present, the gas, the liquid, and the solid. There is only one temperature and one pressure at which such a state of affairs can exist, and the concentration has also a fixed value. Alteration of any factor would cause the disappearance of one of the phases. Such a system has no degrees of freedom.

For the majority of metallic alloys the vapour phase is almost negligible,[3] and as the effect of pressure on the solid and liquid phases is negligible, at least in all ordinary cases where the pressure does not depart largely from that of the atmosphere, the phase-rule equation may be rewritten:

$$f = c + 1 - p.$$

In order to study the application of the phase rule to the theory of the constitution of

[1] See article "Phase Rule," § (3), Vol. I.

[2] Difficulty is often found in understanding the term concentration, although the word is frequently used, and understood, in another sense. For example, we talk of a concentrated solution of salt in water, or of the concentration of a large amount of material into a small space. Thus we see that concentration is closely related to composition but that it is not the same thing—in the case of a gas it is the volume. We may, perhaps, regard the concentration of a component in a phase as the number of molecules per unit volume in the phase. It is important to note that concentration refers to the phase, and is not (necessarily) the composition of the whole specimen containing the phase.

[3] An interesting case where this statement does not hold good is found in the alloys of tin and phosphorus. See "Alloy Systems, Typical," § (12).

alloys, it will be simplest to limit the discussion to the case of binary alloys. Here $c=2$. It will be seen, then, that f can vary from 0, when neither the concentration nor the temperature can be altered without altering the equilibrium of the system, to 2, when either of these factors can be altered independently. When the degree of freedom is 1, the temperature cannot be altered without at the same time altering the concentration, and *vice versa*. Systems with no degrees of freedom are spoken of as invariant, those with one degree of freedom as monovariant, and those with two as divariant.

Applying the rule to the general case of binary alloys, let us first consider a divariant system. Here $f=2$ and $c=2$ and

$$2=2+1-p,$$

therefore $p=1$; that is to say, a divariant binary system can have only one phase. For the monovariant system $f=1$ and $c=2$, therefore $p=2$, or, in other words, when there are two phases the system is monovariant. Finally, if the system is invariant there are three phases present.

(v.) *Interpretation of the Diagram.* — The whole matter may be made clearer by considering the various points, lines, and areas of such a diagram as that shown in *Fig.* 1 in the light of the phase rule. Here there are two components, the metals M and N. c, therefore, is equal to 2. There are also three phases—the liquid phase; the solid phase consisting of M containing more or less N in solution, which may be called the α phase; and the solid phase consisting of N which retains a certain amount of M in solution, and which can be described as the β phase. In the area above the liquidus there is only one phase—the liquid. That is, $p=1$. Then

$$\begin{aligned} f&=c+1-p,\\ &=2+1-1,\\ &=2, \end{aligned}$$

or the system is divariant. In other words, we must specify both temperature and concentration in order that the conditions under which the liquid exists shall be fully specified.

Points between the liquidus and the solidus (*i.e.* the area ABXB′A′, *Fig.* 2) represent alloys containing two phases, a liquid one and a solid one. Applying the equation once more, we find that $f=1$, *i.e.* the system is monovariant, that is to say, we can specify one of the factors (temperature or concentration), but in doing so we fix the other.

Thus, for example, let us consider the alloy whose composition is represented by the line pp' (*Fig.* 2). If now we fix on any arbitrary temperature in that line, say the point t, we have completely specified the condition of that alloy, for we know the concentration of the two phases present, that of the solid phase being given by the point s where the temperature abscissa cuts the solidus, and the concentration of the liquid is given by the

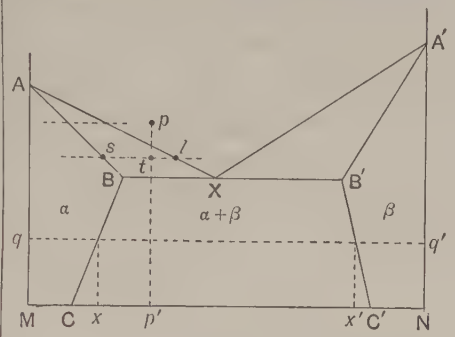


FIG. 2.

similar point l on the liquidus. Similarly, if the concentration l for the liquid is decided upon, the temperature t is automatically fixed. (It must be borne in mind that there are not two independent factors of concentration, one for the liquid and one for the solid, for it is obvious that as the two together must add up to 100 per cent, fixing one automatically fixes the other, so that really there is only one factor for concentration. This applies, of course, only to binary alloys; where the alloy is formed from n constituents, there are $n-1$ factors for concentration.)

Considering next the area CBXB′C′, there are again two phases present, the α phase and the β phase. (It should be noted that the eutectic is not a separate phase, but a mixture of two phases.) As in the crystallisation area, therefore, $f=1$, or the system is monovariant. Referring once more to *Fig.* 2, it will be seen that it is only necessary to specify one of the factors for the system to be completely defined. For example, if the concentration of the α phase is fixed as containing x per cent of N, then there is one, and only one, temperature at which the alloy can be in equilibrium, the temperature denoted by the line qq', and the concentration of the β phase is also fixed as containing x' per cent of N. In the same way, if the temperature q is chosen, then the concentration of the phases is fixed as x and x' respectively.

Not only does the diagram indicate the composition of the phases, but it also shows the amount of each phase present at any temperature. For let x be the percentage of N in the α phase (*Fig.* 3) and x' that in the β phase at the temperature t, and let y be the percentage of N in the alloy, and a and b the

required percentages of the α and the β phases which are present; then

$$\frac{xa}{100}+\frac{x'b}{100}=y$$

and

$$a+b=100.$$

As, then, for any alloy we know y, and can find, from the diagram, the values of x and x' at any temperature, we have sufficient data to solve the two simultaneous equations, and so obtain values for a and b.

These values of a and b can also be obtained graphically from the diagram. For consider any alloy of composition c (*Fig.* 3), at a temperature t. Should the point c coincide with the point d, then the alloy contains 100 per cent of α. If, on the other hand, it corresponds with d', there is 100 per cent of β present, and at intermediate positions the line dd' is divided proportionally to the amount of each phase present. Thus in the case given in *Fig.* 9 the length cd' represents the amount of α in the alloy, while dc is proportional to the quantity of β.

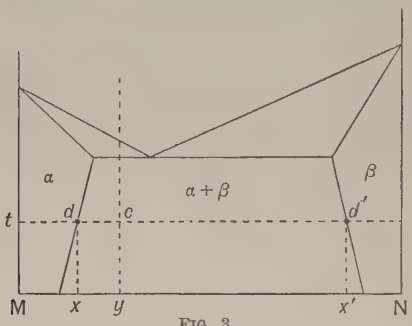


FIG. 3.

There remain the two areas AMCB and A′NC′B′ (*Fig.* 2). In each of these there is one phase only. Therefore $f=2$. That is to say, it is necessary to specify both temperature and concentration before the system is fully defined. For consider any temperature t in this area (*Fig.* 3). The concentration can vary anywhere between pure M, and M completely saturated with N; or if any concentration be chosen, there is a whole range of temperature at which that concentration can exist.

Considering next the various lines on the diagram: the liquidus is the boundary between two areas, one containing but one phase, while the other contains two. One of the phases, the liquid, occurs in both areas, so that at the line there are two phases in equilibrium. Thus the system is monovariant. It is obvious that any sloping line must represent a monovariant system, for on such a line, fixing any temperature fixes the concentration of one of the phases, and conversely. Thus, considering the liquidus, and selecting the temperature represented by the line gf (*Fig.* 4), the concentration of the liquid is fixed as the line *ae*. The same argument applies to the solidus or to any sloping line on the diagram. It must be borne in mind that the only vertical lines which can occur on an equilibrium diagram are those of the constituent metals, which, of course, represent one component system, and therefore do not, strictly speaking, belong to a binary diagram. For it is obvious that on a vertical line we cannot arbitrarily choose either of our factors, for the concentration factor is already fixed, or, in other words, there is not a definite temperature corresponding to the concentration. Therefore the system cannot be monovariant. Furthermore, it cannot be invariant, because it is necessary to specify the temperature in order to fix the system. But any line must represent either invariant or monovariant equilibrium, because there must be at least two phases in equilibrium on the line, from which it follows that the line cannot be vertical, but must have some slope, which, however, may be exceedingly slight.

Horizontal lines, on the other hand, may represent invariant or monovariant equilibrium. As a general rule they are the former.

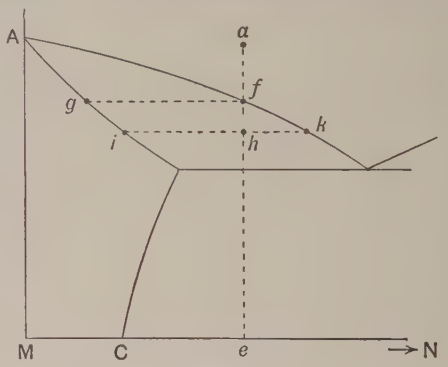


FIG. 4.

Indeed, it is probable that it is only in the case of polymorphic transformations that the horizontal line represents a monovariant system. Any other case, such as the decomposition of one phase, or an eutectic line, is bound to be invariant. For we have three phases in equilibrium at such a line. In the case of the eutectic line these are the liquid phase and the two solid phases forming the eutectic, while in the other case they are the decomposing phase and the two products of decomposition.

Finally, there remain the various points caused by the intersection of lines on the diagram. It is obvious that any point must represent an invariant system, for both the temperature and the concentration are fixed,

and therefore it is not possible arbitrarily to fix either. Thus, for example, at the eutectic point there are the liquid and two solid phases in equilibrium, and therefore $f=0$.

So far we have only considered the existence of two solid phases and one liquid phase. There may be, and in practice generally are, more than this. The case of any single, homogeneous, solid phase is identical with that of the liquid phase or either of the solid solution areas, and the system is divariant.

Similarly, these various phases can occur in groups of two, thus giving rise to monovariant areas, similar to the area CBXB′C′ of *Fig.* 2, and what has been said about this field applies here also.

In addition to this, three phases can exist in equilibrium. The system is then invariant, but, as has been pointed out above, such a state of affairs can only exist at a point or on a horizontal line, and it is impossible to have more than two phases present on an area on the diagram. It can also be seen that more than three phases cannot coexist in equilibrium under any conditions, as this would imply a negative number of degrees of freedom—which is meaningless.

The composition of the liquid and solid phases present at any temperature can be found from the diagram. Take, for example, an alloy denoted by the vertical line *ae* (*Fig.* 4). At the point *a* the alloy is completely liquid. When the point *f* is reached, the liquid becomes saturated with M, and any further cooling causes some of this to separate out. What separates, however, is not pure M but M containing the maximum amount of N which it can retain in solution at that temperature; *i.e.* an alloy whose composition is given by the point *g*, where the temperature abscissae cuts the line AB. The solubility of M in the liquid decreases with falling temperature—the composition of the saturated liquid at any point being given by the intersection of the temperature abscissa and the liquidus. Thus consider the point *h*. The composition of the solid material present is represented by the point *i*, and that of the liquid by the point *k*. From this it will be seen that the sloping part of the solidus curve is part of the solubility curve of N in solid M, while the liquidus is the solubility curve of M in liquid N.

§ (2) Methods of constructing the Diagram.—Almost any measurable properties of a series of alloys may be made use of in the determination of the equilibrium diagram. By far the most commonly used results are those obtained from thermal analysis and from an examination of the microstructure. The theory and technique of both these subjects have been dealt with in other articles,[1] and it only remains to show how the results obtained can be used to construct the diagram.

(i.) *Thermal Methods.*—Assuming that the system under investigation has not been studied before, and that, therefore, nothing is known about it, a number of alloys, say about 20, will be made up and their heating and cooling curves will be taken. The points observed will be plotted on a temperature-concentration diagram, and from this it will be possible to determine a first approximation to the liquidus, parts of the solidus, and any transformations or reactions occurring in the solid. In the case of very simple systems, it may not be necessary to take any more thermal curves, but, generally speaking, the diagram as drawn will indicate regions where further thermal analysis is necessary—to determine, for example, with a greater degree of precision, any singular points on the liquidus.

Quantitative results may be obtained from the thermal curves by using the method, introduced by Tammann, of plotting the length of the various arrests against composition. Thus, suppose the arrests are due to the separation of a compound, the graph should consist of two straight lines intersecting at a point and becoming zero at the two ends. The point of intersection should then correspond with the composition of the compound, which may be fixed in this way, and the points where the lines cut the zero axis will show the limiting compositions of alloys which contain compound, *i.e.* will fix the length of the line representing the separation of the compound. Used with great care, and a realisation of its limitations, this method gives very valuable results, but it has very definite limitations. These are mainly due to two causes. The first of these is caused by the difficulty of accurately determining the points of commencement and end of an arrest. This has already been discussed in the article on the thermal study of metals.[2] A more serious difficulty arises from the fact that it is often exceedingly difficult, and sometimes impossible, to take a curve at such a rate that the alloy remains in equilibrium. In this case the Tammann lines will be those corresponding to the metastable system, which may be very different from the true equilibrium system.

(ii.) *Microscopic Examination.*—The limits of solubility of the various phases will be determined by microscopic examination of annealed and quenched, or slowly cooled and quenched, specimens, and those parts of the solidus which have not been accurately determined by the thermal curves will be investigated in a similar way.

The diagram may not yet be complete. A correlation of the microstructure and the

[1] See "Metals and Alloys, Microstructure of," "Metals, Thermal Study of."

[2] See "Metals, Thermal Study of," §§ (4), (5).

thermal analysis is often necessary to interpret certain lines which may occur, and sometimes it may be necessary to anneal a specimen at a certain temperature for a prolonged time, in order, for example, to induce a sluggish reaction to complete itself, and then to take a heating or cooling curve through a definite range of temperature.

(iii.) *Other Methods.*—Reactions may occur so close together as to be non-separable by thermal methods. It may be that the use of other methods, such as the measurement of electrical conductivity, will enable the two reactions to be distinguished separately, but often they must be fixed from theoretical considerations. These theoretical considerations must always be kept in mind during the investigation of an alloy system, as there are many pitfalls awaiting the investigator who neglects them, or who is content with the study of an insufficient number of alloys.

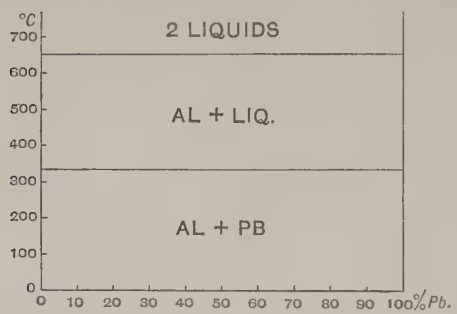


FIG. 5.—Al-Pb Alloys (Gwyer).

There is no simple and definite course which can be laid down beforehand in the investigation of an alloy system. As in a game of chess there are recognised openings, after which the game develops according to circumstances, so there are definite openings in the establishment of the equilibrium diagram; but once these are made the next moves must be dictated by the results already obtained.

§ (3) TYPES OF BINARY DIAGRAM.—(i.) The very simplest type of alloy system is that in which both the components are completely insoluble in each other, both in the liquid and in the solid state. While complete insolubility is theoretically impossible, yet a very close approach to it is found in certain alloys. Thus *Fig.* 5 shows the constitutional diagram of the alloys of lead and aluminium.[1] In this case the two liquids cool together till 658° C. is reached, when nearly pure aluminium solidifies, then the temperature falls once more, and at 327° C. the remainder of the alloy becomes solid by the deposition of practically pure lead.

[1] Gwyer, *Zeit. anorg. Chem.*, 1908, lvii. 113.

(ii.) Conditions exactly opposite to those just discussed give rise to another very simple type of diagram. In this case the metals, both in the liquid and the solid state, are

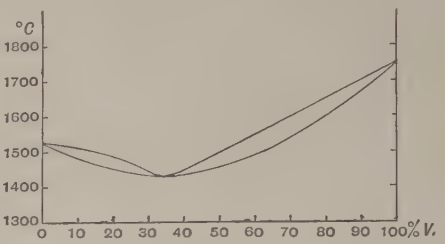


FIG. 6.—Fe-V Alloys (Vogel and Tammann).

completely soluble in each other, and the diagram takes the form of either *Fig.* 6, *Fig.* 7, or *Fig.* 8. (In practice, *Fig.* 7 has not yet been found.) The liquidus and the solidus

FIG. 7.

are smooth curves which are both concave upwards, both concave downwards, or one is concave upwards and the other downwards.

Fig. 6 represents the constitution of the iron

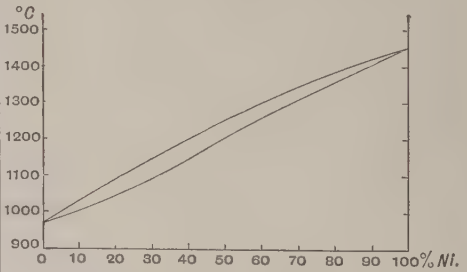


FIG. 8.—Cu-Ni Alloys (Guertler and Tammann).

vanadium alloys, while *Fig.* 8 shows that of the copper-nickel alloys.

(iii.) An intermediate type is found in the case of metals which are completely soluble in each other in the liquid and only partially soluble in the solid. This type can be divided

into two classes—(*a*) those in which no eutectic is formed and (*b*) those in which an eutectic is formed. It would probably be more accurate to define the former case as one in which the eutectic point occurs very close to one end of the diagram. In such a case the solubility in the solid state must be excessively small.

Fig. 9 (aluminium-tin alloys) is an example of the first case, while the silver-copper alloys [1]

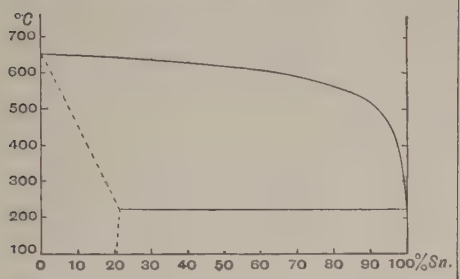


FIG. 9.—Al-Sn Alloys (Gwyer).

furnish an example of the second. In neither of these systems has the solubility been accurately determined.

(iv.) In yet another type, the liquidus consists of two branches which meet at a point lying above the melting-point of one of the constituent metals. The point of intersection also lies on a line, along which the first deposited solid reacts with the liquid to form a new solid phase. Zinc, containing small quantities of copper, gives rise to a diagram of this type.[2]

(v.) In a large number of alloy systems intermetallic compounds are formed. Such systems may be divided into two main groups :

(*a*) The compound has a definite melting-point.

(*b*) The compound dissociates at a temperature below the liquidus.

In the former case the diagram can be regarded as forming two systems, one of the metal M with the compound M*x*N*y*, and the other of the metal N and the compound. Each of these systems may, if simple enough, be classified as above. Similarly, if there are two undissociated compounds, the alloys can be divided into three systems. The aluminium-magnesium system [3] is an example of such a series.

In such cases the compound is easily recognised, as it is generally indicated by the existence of a maximum on the liquidus, though occasionally it takes the form of a break in the curve, as for example in the alloys of magnesium and cadmium (*Fig.* 10).

When, however, the compound dissociates at a temperature below the liquidus, its composition is not nearly so easy to determine, as this is not shown by any maximum on the liquidus, and the break which occurs in the curve will not in general correspond to the composition of the compound, but to the composition at which the co-ordinate corresponding to the dissociation temperature cuts the liquidus. The compound Al_2Zn_3 [4] may be taken as typical of this phenomenon.

All the cases considered so far have been simple, but in practice such simple systems are rare, and a diagram may be built up of many types added together. Such a system may be very complex, as will be realised in considering the copper-aluminium, copper-tin, or copper-zinc diagrams.[5] Further complications, examples of which can be seen in each of these systems, are introduced by reactions occurring in the solid, or by allotropic or polymorphic transformations. These cases are considered in the article dealing with typical alloy systems.

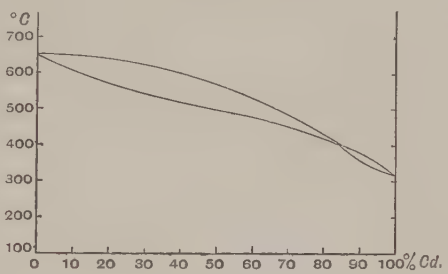


FIG. 10.—Cd-Mg Alloys (Grube).

§ (4) METHODS OF REPRESENTING TERNARY EQUILIBRIA.—As we have seen, the constitution of a binary system may be represented by a plane diagram, *i.e.* a diagram in two dimensions. The composition can be represented by a single dimension, because the specification of the proportion of one of the components automatically fixes the proportion of the other. In a ternary system, on the other hand, it is necessary to specify the percentage of two of the components before the composition is fully defined. From this it follows that in any graphical representation two dimensions are necessary to represent the composition, and therefore the temperature-concentration diagram has to take the form of a three-dimensional model.

To represent the composition of a ternary series of alloys it is not usual to employ rectangular co-ordinates, though this can be done. For example, in *Fig.* 11 the composition of alloys of the metals L, M, and N is represented. In this case the points A, B, C,

[1] "Alloy Systems, Typical," § (8).
[2] *Ibid.* § (2).
[3] *Ibid.* § (7).
[4] "Alloy Systems, Typical," § (5).
[5] *Ibid.* §§ (2), (3), (4).

D, E, and F will represent alloys of the following composition :

Alloy.	L.	M.	N.
A	70	20	10
B	60	40	0
C	40	0	60
D	0	60	40
E	30	40	30
F	20	10	70

It will be seen that the points representing the alloys of L and N (*i.e.* those containing no M) lie on the line LN, and the disadvantage of this method of plotting is due to the fact that this line is not of the same length as the

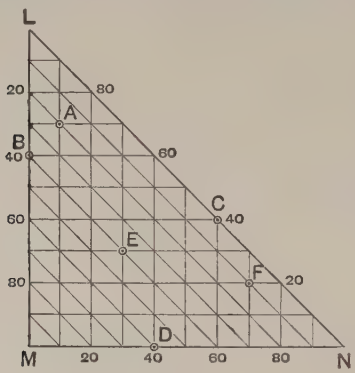


FIG. 11.

lines LM and MN, or, in other words, that the percentage of M present is represented on a different scale from that of the other two components.

(i.) *Trilinear Co-ordinates.*—To overcome this difficulty the system of trilinear co-ordinates has been introduced. This system is based on the fact that in an equilateral triangle the sum of the perpendiculars to the sides of the triangle from any point within it is a constant, and is equal to the height of the triangle. If such a triangle whose height is equal to 100 units is constructed, the perpendiculars drawn to the sides from any point within the area will then add up to 100. If now the corners of the triangle be regarded as representing 100 per cent each of the component metals, the length of each perpendicular from any point within the triangle to the side will represent the percentage of the metal indicated by the corner opposite that side.[1]

[1] This method was proposed by Gibbs. Another method, suggested by Roozeboom, which gives exactly the same result as Gibbs's method, consists in employing an equilateral triangle, each of whose sides is divided into 100 equal parts.

Thus in *Fig.* 12 the alloys which were shown in *Fig.* 11 are replotted on a triangular diagram. It will be seen that points lying along the sides of the triangle represent alloys containing only two components, while

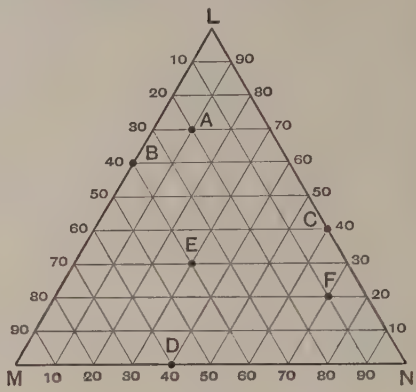


FIG. 12.

points inside the triangle correspond to ternary alloys.

Having fixed on a method of representing the composition of a series of ternary alloys, it is now possible to represent temperatures by erecting, from the triangle, perpendiculars whose height is proportional to the temperature. In this way the liquidus of a ternary system, which in a binary system took the form of a number of lines at definite heights above the base line, becomes a number of surfaces at definite heights above the base triangle. Similarly the solidus is represented by another series of surfaces, one of which, in the case of a series containing one ternary eutectic, is horizontal and touches the liquidus surfaces at one point, the ternary eutectic point. The whole system, in fact, takes the form of a solid triangular prism cut up into numerous sections by plane or curved surfaces, horizontal, vertical, and inclined.

(ii.) *Solid Models.*—The representation of such a system by means of a solid model is by no means easy. It has been done by employing a plaster of Paris model which can be dissected into a number of solids, each of which represents a phase area in the model. This method has the great disadvantage that it is not possible to see more than a very few of such areas at a given moment, which renders it difficult to realise the way in which they are correlated. Recently, however, it has been shown that it is possible to build up a model with wires in such a way that each surface is marked off with a series of wires.[2] This method has the

[2] "A Model for representing the Constitution of Ternary Alloys," by W. Rosenhain, F.R.S., *Inst. of Metals J.*, 1920, xxiii. 247.

great advantage that it is possible to see all the planes at the same time, and thus the complete correlation of the various reactions is rendered much easier to grasp. For full details of the method reference should be made to the paper quoted above.

While the representation of any system of ternary alloys is rendered possible, if not easy, by this method, the problem of reproducing such a model in the two dimensions allowed in a book is exceedingly difficult. It is, of course, possible to photograph the model, but even in the case of a very simple system the superposition of a number of

This method, as well as the photographic one, suffers from the defect that the model is represented in perspective, hence accurate measurement of temperatures and compositions becomes very difficult, and while it is the best method yet devised for representing a general view of the constitution, other ways have to be used to give accurate data from which measurements can be taken. One way is to draw a large number of plane sections through the model. Those can be chosen parallel to one or other of the sides of the triangular prism, in which case each section will represent the constitution of a series of

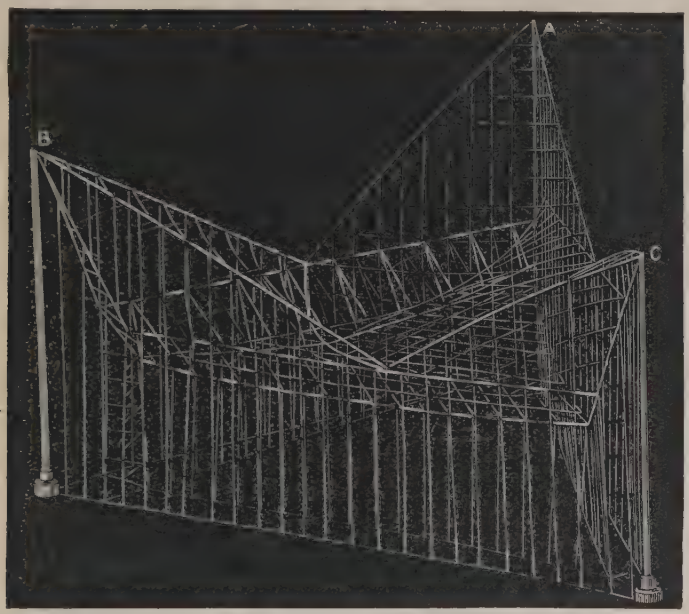


FIG. 13.—A Model for representing the Constitution of Ternary Alloys.

planes makes it very difficult to realise which lines belong to which planes, and a considerable amount of confusion arises from this superposition. An examination of the photograph of the simple model in the paper referred to above (*Fig.* 13) amply confirms this statement.

Much greater clearness will be obtained by making a series of drawings of the model and emphasising one surface or set of surfaces on each drawing. Thus the first diagram may have the liquidus surfaces drawn in in heavy lines and shaded, the rest of the drawing being made very very faint. In a second figure the solidus surfaces will be shaded, while a third picture will show planes denoting other reactions or transformations (see *Figs.* 14, 15, and 16 [1]).

[1] *Figs.* 13, 14, 15, and 16 are reproduced, by kind permission, from the paper referred to on p. 252.

ternary alloys in which one of the constituent metals is present in a constant proportion; or they can be made along lines radiating from one or other of the corners of the triangle. In this case each section will represent a series of alloys in which the ration of two of the metals is constant.

Again, the sections can be drawn parallel to the base of the prism, *i.e.* they will be constant temperature sections.

In both these cases, more especially in the latter, it is necessary to show a large number of sections if an accurate representation of the model is required, especially should the latter be complicated, and to avoid this necessity another method of representation can be employed. The various planes which have been emphasised in the drawings referred to above can be projected on to the base,

and contour lines drawn on them to indicate their temperatures (*Figs.* 17, 18, and 19). In tures are not required, all the planes can be projected together on to the base (*Fig.* 20).

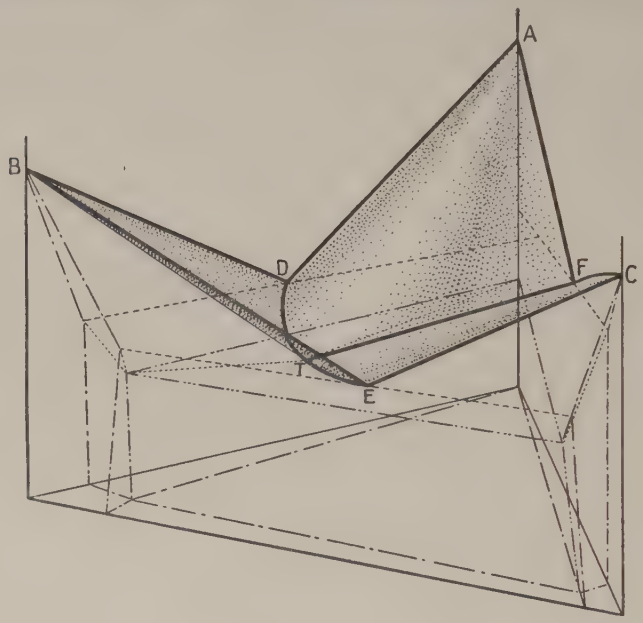


Fig. 14.

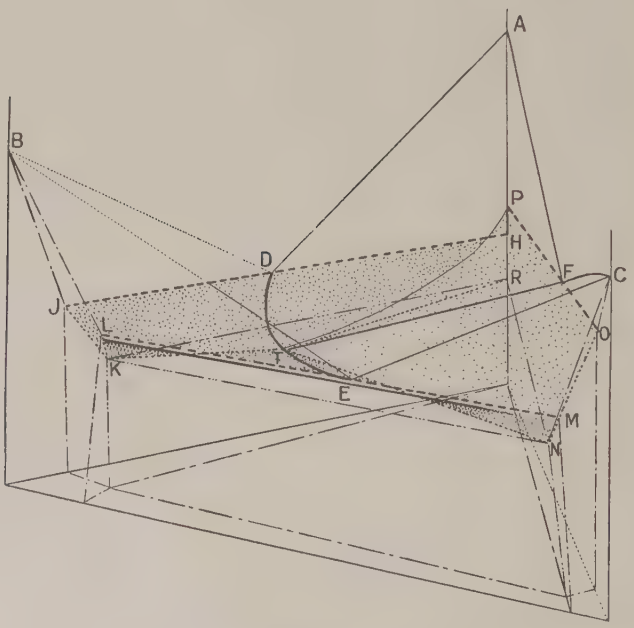


Fig. 15.

general, three or four such diagrams will represent a complete system. Where tempera-

§ (5) Different Types of Ternary Systems. — A complete discussion of the

different types of ternary diagrams which can occur would take up too much room to be possible here. For a partial discussion of the subject the reader is referred to the book on *Metallic Alloys*, by G. H. Gulliver. Briefly, however, it may be stated that ternary alloys may be classified in the same way as binary alloys, additional complications being introduced by the fact that ternary eutectics may be formed, and that it is possible to have present both binary and ternary compounds.

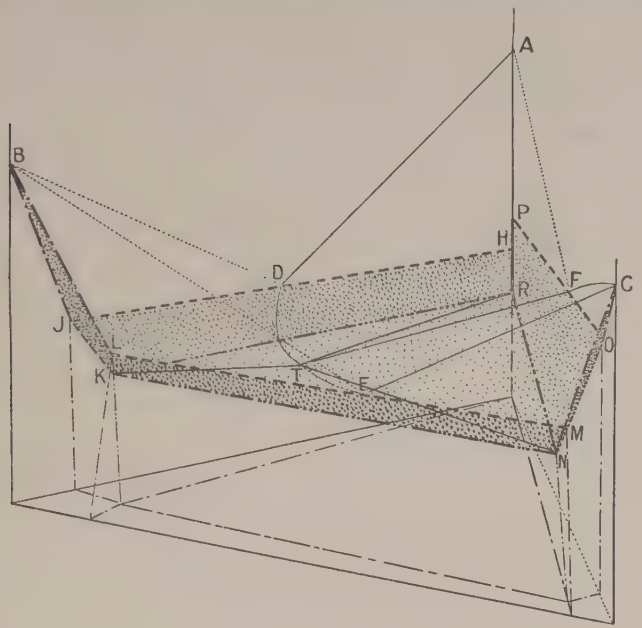


FIG. 16.

§ (6) QUATERNARY SYSTEMS.—While the composition of a binary system of alloys can be represented on a straight line (one dimension), and that of a ternary system on a plane diagram (two dimensions), it is necessary to employ a solid model (three dimensions) to represent the composition of a quaternary system. The composition diagram of the ternary system is constructed by joining up the straight lines representing the compositions of the component binary systems in such a way as to form with these the boundaries of an equilateral triangle. In the same way the four component ternary triangles of a quaternary system can be joined up so as to

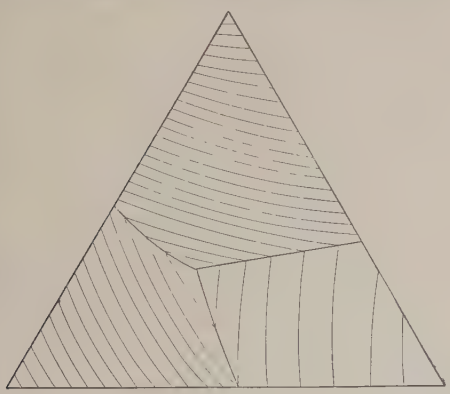


FIG. 17.

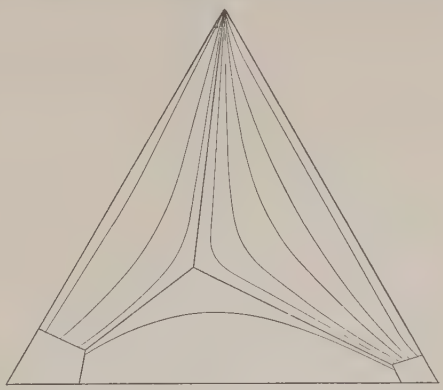


FIG. 18.

form a regular tetrahedron. This figure has four corners, representing the four component metals, six edges, which represent the six binary systems, and four faces, which correspond to the four ternary component systems.

Having used up the three available dimensions to represent the composition, it follows that it is not possible to construct a model connecting composition and temperature. There are, however, methods for representing the constitution which are strictly analogous to the representation of a three-component system on a plane surface. In the first place, it is possible to make a number of " sections " through the imaginary four-dimensional model. If these " sections " are made in such a way that they lie along a solid containing a constant amount of one of the components (for a " section " through a four-dimensional

FIG. 19.

system is a solid), then each of them will be a ternary prism, where the basal triangle will represent three variable components + one fixed one, and a sufficient number (which may have to be very large) of such prisms will represent the constitution of the system.

If, on the other hand, these " sections " are cut so as to represent constant temperatures, the figures so obtained will be a series of regular tetrahedra, each representing the constitution of the alloys at a particular temperature, and, again, a sufficient number of such models will represent the constitution of the series.

There is, however, another method which can be employed, and which has the advantage that it will require fewer models to represent the series completely. We have seen, in the case of ternary systems, that the whole model can be represented, with quite a small number of diagrams, in two dimensions by projecting, on to the composition base, one set of surfaces at a time, and drawing contour lines on them. The quaternary " model " can be treated in a similar way. Consider, for example, the liquidus " surface " of such a model. The projection of this will be a regular tetrahedron in which the various compartments represent the compositions over which the different primary separations commence to crystallise. It remains to fix the temperature of those separations. In the ternary system this was done by drawing contour lines on the projected areas. These contour lines will be replaced, in the quaternary system, by contour surfaces. If the projected model were built up of wire, those contour surfaces could be made of much finer wire distinctively coloured. Other models would represent the commencement and end of solidification of binary eutectics, and of ternary eutectics, the solidus region and reactions in the solid.

As yet no quaternary system has been

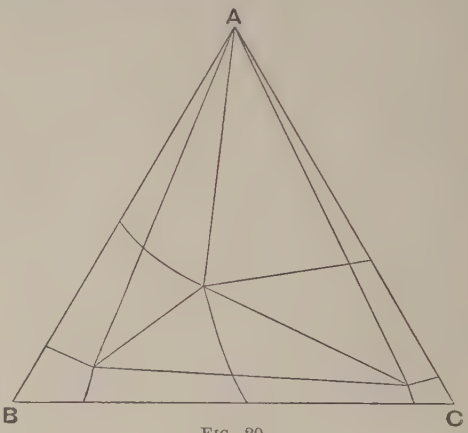


FIG. 20.

thoroughly worked out, and the various types that can occur have not been discussed. That the alloys can be very complicated is obvious when it is remembered that in a very simple system it is possible to have six binary eutectics, four ternary eutectics, and one quaternary eutectic. Of those the quaternary is the only true eutectic, as the others have a variable composition and solidify over a range of temperature. The composition of the ternary complexes (to use a better term) will vary along a line, while that of the binary complexes will vary over an area.

§ (7) MORE COMPLEX SYSTEMS.—The composition of alloys containing five or more components cannot be represented in three-dimensional space, and the only way of dealing with them is to consider the system as being composed of a large number of quaternary systems each containing a constant amount of the remaining metal or metals. Up to the present no such system has been investigated.

§ (8) USES OF THE EQUILIBRIUM DIAGRAM.—The uses, and the limitations, of the equilibrium

diagram are many. In the first place, it gives, in a form which is convenient and readily understood, a picture of the constitution of a series of alloys which could not be conveyed by words without extreme difficulty. But beyond its value as a contribution to the theoretical study of alloys the diagram has a considerable practical value. As will be seen further on, there is a close connection between the physical properties and the constitution of alloys. In general terms, it may be stated that a metal consisting of an α phase only (see § (1) (iv.)) is, as a rule, ductile, and can be rolled into sheet or drawn into wire without the application of heat; that duplex alloys (those containing α and β phases) are generally harder, stronger, and more brittle, and usually require hot working; while alloys containing a γ phase will, in general, be too brittle to be of much use. Intermetallic compounds are also, in general, very hard, brittle substances whose presence, in more than very small quantities, should be avoided except for very special purposes.

From these considerations, and a knowledge of the constitution of an alloy system, it is possible to predict, more or less accurately, the range of alloys in that system which are likely to be of commercial value. Thus, in the case of a series like that of copper and nickel, where the two metals are completely soluble in each other in the solid state, that is, any alloy in the system is a homogeneous α phase, it could be deduced that the whole series would give rise to workable, ductile materials, while in the copper-tin system, for example, where the α phase does not extend much beyond 10 per cent of tin, it would be safe to suggest that about 15 per cent of tin would be the limit of the generally useful alloys.

If a transformation takes place in a series of alloys, the mechanical properties of the material quenched from above the transformation temperature may be very different from that of the same material cooled slowly through the transformation. In such a case the equilibrium diagram will give valuable information as to the required quenching temperature, etc. The iron carbon alloys furnish a notable example of this.

It must be borne in mind, however, that the equilibrium diagram only shows the condition of a series of alloys in equilibrium, and gives no indication of the time required to reach that state. Referring once more, for example, to the copper-tin alloys, it can be seen from the diagram (p. 225) that an alloy containing 10 per cent of tin should consist of homogeneous α solid solution. If, however, almost any commercial alloy containing this amount of tin be examined, it will be found to be duplex, and an annealing of several hours' duration will be necessary to render it homogeneous. It must be noted, however, that the diagram will furnish evidence as to what phases may be present in a metastable alloy, even though it does not define the conditions necessary to attain that equilibrium. Thus in the copper-tin alloy under discussion the diagram will show that the metastable constituent above 500° C. is β, but that at this temperature the reaction $\beta = \alpha + \delta$ takes place. In the case of a very rapidly cooled alloy we shall expect to find α + metastable β, while if the cooling is less rapid the material will consist of α + metastable $(\alpha + \delta)$. This latter is what is generally found in commercial samples of 10 per cent bronze. J. L. H.

ALLOYS, THE RELATIONSHIP OF STRUCTURE AND PHYSICAL CONSTANTS

§ (1) Physical Properties of Alloys.—The physical properties of alloys are closely connected with their constitution. It may in general be said that, on passing from one phase field of a constitutional diagram to another, the curve connecting composition with any physical property will show a discontinuity or singular point. It follows, therefore, that a knowledge of the equilibrium diagram will be a guide in the investigation of the physical properties, both with regard to the treatment to which metals or alloys should be subjected before making the measurements and to the results which may be expected owing to variation of composition and heat treatment.

A very great deal of work has been carried out in the past on the physical properties of metals and alloys which is practically useless, or even misleading, because the investigators have not realised to how great an extent the properties which they have been measuring are influenced, not only by composition, but also by heat and mechanical treatment, in other words, to what an extent they are dependent upon the constitution.

Evidence for this can be found in the very contradictory results given by different workers for what is supposed to be the same material. Thus two different tables give the electrical resistance of "brass" as $5{\cdot}5 \times 10^{-6}$ and 8×10^{-6} ohms per cc. respectively. In the first place it must be noted that the word "brass" covers a whole series of alloys whose constitution, and therefore specific resistance, varies over wide ranges even when they are pure and in a state of equilibrium at the temperature at which the measurement is made. Secondly, even when a complete chemical analysis of a material is given, it is by no means completely specified, as the previous thermal and mechanical history may have a very considerable influence on the constitution, and therefore, once more, on the specific resistance.

In the past results have frequently been obtained out on alloys made by melting the constituent metals together and casting the resulting material. It cannot be too strongly emphasised that such results may be utterly valueless unless full data of the rates of cooling, etc., are given, or unless the materials are annealed so as to be in a state of equilibrium at the temperature of the test. Physical property measurements, to be of any value, must be made on alloys which have been properly annealed, unless, of course, the material is stated to be worked, or otherwise treated, in which case the treatment must be fully specified. That a condition of proper annealing has been reached may often be deduced from microscopic examination, or it may be ascertained by measuring the physical property at repeated intervals, each measurement being carried out after a definite annealing. When further heat treatment produces no alteration in the value obtained by the measurement, the presumption is that the value is an equilibrium one.

In the present article the investigations of physical properties have been considered from the point of view of their use in establishing the equilibrium diagram rather than from the converse point of view. The reason for this is partly that, except for the measurement of certain properties, such as electrical resistance at room temperatures, the investigations have generally been carried out in connection with the study of equilibria, and partly because it enables the pros and cons of these methods, from the point of view of establishing the diagram, to be considered, without in any way hampering the consideration of the effect of constitution on the physical properties.

The principal physical properties which have to be considered in this connection are: (1) Electrical conductivity, (2) thermal conductivity, (3) thermal electromotive force, (4) specific volume, (5) specific heat, (6) electrolytic potential, (7) magnetic properties, (8) those properties which are generally grouped under the head of mechanical properties, *i.e.* elastic limit, yield point, maximum strength, elongation, hardness, etc.; (9) Hall and Nernst effects, (10) photo-electric effects and other optical properties.

Of these the mechanical properties are so important that they are considered separately (*vide* article "Metals, Relation of Strain and Structure") and, with the exception of hardness, will not be discussed in any detail here. It may be mentioned, however, that the modulus of elasticity of metals does not appear to be appreciably altered by alloying, which suggests that the modulus is a property of the atom and is not dependent on its arrangement. Of the other properties, some, *e.g.* magnetic properties, are limited to a few alloys and others — the photo-electric properties, for example—have been very little studied.

§ (2) Electrical Conductivity.—The electrical conductivity of a series of alloys is very intimately connected with their structure and, next to thermal and microscopic methods, its study is the most useful method of attack for investigating constitution. It also has the advantage that from one set of experiments three different types of curves can be plotted, each of which may throw light on the constitution of the alloys under observation. For example, suppose a series of alloys to have been made and their electrical conductivity, or its reciprocal, the electrical resistance, to have been determined over a temperature ranging, say, from above the liquidus to room temperature. Curves can be plotted for each alloy connecting temperature and conductivity, and these curves can be used in the construction of the diagram in exactly the same way as thermal curves are used. They have, however, certain advantages over thermal curves, which will be considered below. Secondly, from the observations the temperature coefficient of resistance can be calculated for each alloy at varying temperatures, and for each temperature a curve can be drawn connecting the temperature coefficient with composition. These curves will show breaks or changes in direction on the passage from one phase field to another, and in this way vertical, or nearly vertical, lines on the diagram will be indicated. In both these methods the absolute value for the resistance is not required, and therefore the exact dimensions of the specimens are unimportant. The third method, which is the one most generally used, and is probably the least satisfactory, consists in plotting the absolute resistance at any temperature against the composition. The curves thus obtained are used in the same way as those relating to the temperature coefficient, but in this case the dimensions of the specimens must be accurately known, and the material must be free from any flaws, blowholes, etc. This limits the method to alloys which can be worked and also which can be either cast free from blowholes or can be rolled or wire-drawn so as to close up any holes which may have formed on casting.

As a means of investigating the constitution of a series of alloys, the study of electrical conductivity shares, with other physical property measurements, certain advantages over thermal analysis. One of these is that the conductivity measurements can be carried out at any desired slowness, and so equilibrium conditions are much more readily attained. Further, conductivity curves will indicate steeply sloping lines on the diagram, such as

solubility limits, while it is very rare to find evidence for the crossing of such lines on thermal curves.

It is possible, and indeed advisable, to plot the curves connecting composition with both conductivity and resistivity. The former, in general, indicates discontinuities more clearly, while the latter is usually more nearly linear.

It appears to be a universal rule that alloying lowers the electrical conductivity of metals. This is most marked where solid solutions are formed. It has been suggested that this may be due to Peltier effects [1] at couples formed in the alloys. This theory is, however, no longer held.

The types of electrical conductivity-composition [2] curves found in alloy systems may be divided into three classes: (1) Straight, or nearly straight, lines are generally found in heterogeneous regions, such as eutectics, though it is stated that differences in the arrangement of the phases will introduce small deviations from this linear arrangement. (2) Solid solutions give rise to a steeply falling curve. The curve falls much more rapidly with the first addition of the alloying metal. Where the alloys form an unbroken series of solid solutions, the curve takes the form of a deep, flat-bottomed U. (3) The presence of an intermetallic compound causes a sharp cusp, generally, though not invariably, pointing upwards. The conductivity of the compound is always less than that of the component having the higher conductivity, though it *may* be greater than that of the other constituent. It is also invariably lower than that calculated by assuming a rectilinear relationship between composition and conductivity. The passage from one phase field to another generally causes an abrupt change in the direction of the conductivity-composition curve. This fact has been used to determine the limits of solubility of one metal in another.

The temperature coefficient behaves in the same way as the conductivity, *i.e.* the curve connecting temperature coefficient and composition is linear in mixtures and U-shaped in a series of solid solutions; the former is frequently expressed in metallographic work as the percentage decrease of conductivity between 0° C. and 100° C., and is termed P. For pure metals P has a value varying from 27 to 31. For intermetallic compounds it is somewhat smaller, being 22 for the compound CuSn, while for solid solutions it may be zero, or in rare cases, negative.

There are few systems whose electrical conductivity has been carefully worked out. *Fig.* 1 A represents the diagram for the alloys of magnesium and cadmium, [3] and *Fig.* 1 B is the curve of electrical conductivity of the series at 25° C.[4] At each end of the diagram are the descending branches of the U-shaped curve, due to the β solid solution. This U,

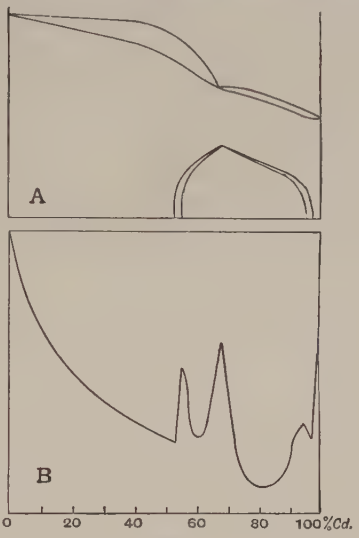


Fig. 1.

however, is interrupted by the appearance of the α solution, which is the compound MgCd in solution in the component metals. In the narrow regions where α and β coexist the conductivity rises linearly, while the two

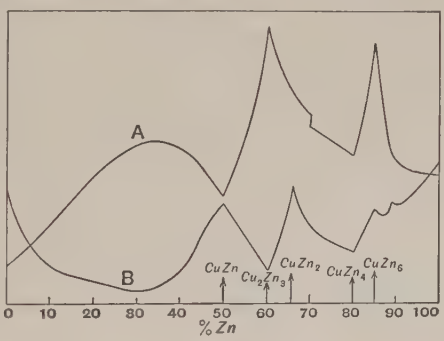


Fig. 2.

U-shaped branches are due to the solutions on either side of the compound, which, itself, is indicated by a sharp cusp.

Fig. 2 A indicates the electrical resistivity and *Fig.* 2 B the temperature coefficient of resistance of the alloys of copper and zinc: [5]

[1] Rayleigh, *Nature*, 1896, liv. 154.
[2] The composition used should be composition by volume and not by weight.
[3] Grube, *Zeit. f. anorg. Chem.*, 1905, xlix. 72.
[4] Urasow, *Zeit. f. anorg. Chem.*, 1912, lxxiii. 30.
[5] Pushin and Rjaschsky, *Zeits. f. anorg. Chem.*, 1913, lxxxii. 50.

these can be compared with the diagram given on p. 223.

Finally, *Fig.* 3 is a temperature resistivity curve for an alloy containing 37 per cent Cu and 63 per cent Sn.[1] It shows the break due

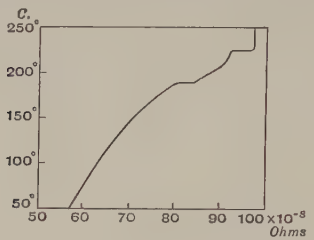


Fig. 3.

to the solidification of the eutectic and to a polymorphic transformation in the ϵ constituent (see p. 225).

The fact that the formation of solid solutions causes a rapid rise in resistivity can be used to determine the purity of a metal. Owing to the increase in purity of copper refined by electrolytic methods over that in use when Matthiessen introduced his copper standard, commercial copper can now be obtained whose conductivity, expressed in terms of the Matthiessen standard, is 101 per cent.

It has been shown that the addition of different elements to iron raises its resistivity in proportion to the atomic percentage of the added element, provided it is present in solid solution. For such elements, the resistivity of the alloy in microhms per cubic cm. is $R = 7{\cdot}6 + 26{\cdot}8\Sigma C$, ΣC being the dissolved carbon + the carbon equivalent of the other elements.[2]

§ (3) Thermal Conductivity.—Wiedemann and Franz [3] have shown that the quantity λ/κ of the ratio Thermal Conductivity/Electrical Conductivity has a constant value of about 1·36 for pure metals at a given temperature. Lorenz,[4] however, has demonstrated that this is not strictly true, but that the ratio increases with temperature. Further work on this subject has been carried out by Jager and Dieselhurst [5] and Lees.[6] For solid solutions λ/κ is higher than for pure metals, and it is still higher for compounds. From this it follows that alloying does not affect the thermal conductivity to nearly as great an extent as it affects the electrical conductivity. As an example, it may be mentioned that the thermal conductivity of aluminium [7] is 0·5, while that of an alloy containing 8 per cent Cu, 1 per cent Ni, and 91 per cent Al has a thermal conductivity [7] of 0·4. This fact has made certain of these alloys extremely valuable for use in the manufacture of internal combustion engine pistons.[8]

Owing to the similarity of the results obtained by electrical and thermal conductivity measurements, and to the much greater ease of obtaining the former, the latter have been very little employed in metallographic work.

§ (4) Thermal E.M.F.—Perhaps next in importance to the study of electrical conductivity is that of the Thermal Electro-motive Force generated between the members of a series of alloys with some standard metal, though the curves obtained by this method are not always as easy to interpret as those obtained from the study of electrical resistance. The reason for this will be seen later.

The results obtained from the study of the thermal E.M.F. of a series of alloys may (as in the case of the study of electrical conductivity) be plotted in three ways. Observations can be taken on a series of alloys, in each sample of which the thermal E.M.F. against a standard metal is observed when one junction is kept at 0° C. (or some other convenient temperature), and the other is gradually raised to the melting-point. Or a constant difference of a few degrees can be kept between the two junctions, and both gradually raised. In this way the ratio de/dt, the thermo-electric power of the couple, is observed. The curves obtained in either of these ways can be used in the construction of the diagram in the same way that thermal curves are used. On the other hand, the E.M.F. of the series of alloys can be obtained against a standard metal, one junction being kept at zero and the other at a definite temperature, say 100° C., and the results obtained are plotted against composition.

As in the case of electrical conductivity-composition curves, heterogeneous regions tend to give a straight line, and homogeneous regions a curve, when the thermal E.M.F. is plotted against the composition, but it is necessary to plot the composition by volume and not the composition by weight. Now, as will be shown later, the volume of an alloy is not necessarily the sum of the volumes of its components, and it is therefore necessary to find out the curve of specific volumes of the series before the thermal E.M.F. is studied if conclusions from the general shape of the curve are to be drawn. In addition

[1] Haughton, *Faraday Soc. Trans.*, 1920.
[2] Benedicks, *Zeits. f. phys. Chem.*, 1902, xl. 545.
[3] Poggendorf's *Annalen*, 1853, lxxxix. 497.
[4] *Ann. der Phys.*, 1882, xiii. 422.
[5] *Preuss. Akad. Wiss.*, July 1899.
[6] *Roy. Soc. Phil. Trans.*, 1905, cciv. 433; 1908, ccviii. 381. See also article on "Heat, Conduction of," § (10) (i.), Vol. I.

[7] These figures are gram calories conducted per sq. cm. per second across a slab 1 cm. thick having a temperature difference of 1° C. per cm., the tests being carried out at 100° C.
[8] *Vide* article on "Aluminium Alloys," § (2).

to this, it has recently been shown[1] that the arrangement of the constituents in an alloy affects the thermal E.M.F., which it will generate in contact with a standard metal, so that irregularities may be introduced into the curve in this way. This is one of the causes of difficulty in interpreting the results obtained by the study of thermal electromotive force in terms of the equilibrium diagram. Another difficulty is introduced by the fact that in some cases the formation of a solid solution raises the thermal E.M.F. (against a standard metal), and in other cases lowers it, while in certain cases it raises it at one temperature and lowers it at another.[2] At a temperature intermediate between these two, the E.M.F. will be unaffected by alloying, and therefore the curve connecting E.M.F. and composition will be a straight line at that particular temperature, as though the alloys were heterogeneous and not homogeneous. These considerations, however, only apply to curves connecting E.M.F. with composition, and not to curves only connecting E.M.F. with temperature.

The theoretical reasons underlying the shape of the curve for solid solutions cannot be said to be known. It has been suggested that it is due to the formation, in solid solutions, of couples of which the E.M.F.'s are added together, these causing the thermal E.M.F. to vary. This is not, however, proved.[3]

In *Fig.* 4 is given the curve connecting the thermo-electric power and composition of the

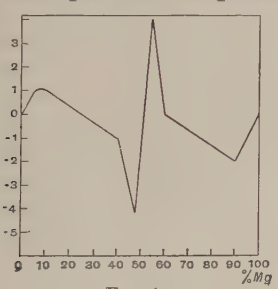


FIG. 4.

alloys of aluminium and magnesium.[4] If this is compared with the diagram,[5] it will be seen that:

(i.) Up to about 10 per cent Mg this is a curve corresponding to the solid solution α.

(ii.) From 10 per cent to about 40 per cent Mg the graph is rectilinear, corresponding to the heterogeneous field $\alpha+\beta$. (Enough points are not taken to indicate the narrow field of pure β between 35 per cent and 38 per cent Mg.)

[1] Haughton, *Institute of Metals Journal*, 1920, xxiii. 499.
[2] Broniewski, *Ann. de chem. et phys.*, 1912, xxv. 5.
[3] *Ibid.* [4] *Ibid.*
[5] "Typical Alloy Systems," *Fig.* 10, p. 231.

(iii.) Between 40 per cent and 48 per cent Mg the graph is again rectilinear, though the slope is very different. This represents the heterogeneous field $\beta+\gamma$.

(iv.) From 48 per cent to 56 per cent Mg the graph rises very rapidly, and then falls away again to about 60 per cent. This corresponds to the separation of the compound forming the solid solution γ. Again, there are not enough points accurately to determine whether this part of the graph consists of a smooth curve or two intersecting straight lines—theoretically, it should be the former.

(v.) In the next region the straight line between 60 per cent and 90 per cent Mg corresponds to the heterogeneous field of $\gamma+\delta$, while

(vi.) Between 90 per cent and 100 per cent Mg the relationship should be expressed by a curved line. As, however, only two points were observed in this region, it is impossible to say what the shape actually is.

It will be seen that the curve is plotted against compositions in weight per cent instead of volume per cent. The specific volumes of the series have not been sufficiently accurately determined to make it advisable to use the latter method of plotting, and this may account for some of the slight discrepancies between the thermal E.M.F. results and the equilibrium diagram.

Thermo-electric measurements have been made on both pure metals and alloys with a view to studying the effect of annealing hardened material. If a wire, hardened by work, is connected with a similar wire, which has been annealed, and the junction is heated, a thermo-electric force is generated. If the temperature is gradually raised, a point is reached when the work-hardened material commences to anneal, the E.M.F. falling off rapidly at this temperature, and becoming zero when the material is completely annealed.

§ (5) SPECIFIC VOLUME AND THERMAL EXPANSION.—The study of Specific Volume, or its reciprocal, Specific Density, does not throw very much light on the constitution of a series of alloys, although the study of the volume changes in an alloy, measured by means of its expansion when heated, is very useful in the determination of allotropic or polymorphic changes, and this method could, no doubt, be used for detecting other changes (due to transformations or reactions, for example) which occur in alloys. The method has, however, no marked advantages over electrical conductivity measurements or the study of thermal electro-motive forces, while there are several disadvantages inherent in the use of this property. In the first place, it is almost impossible to investigate the thermal expansion of materials between the liquidus and the solidus. A large amount of work on the

volume changes undergone by alloys on cooling from the liquid has been carried out by Turner and others, but the results, though in many cases of great practical value, are influenced by so many factors that they are extremely difficult to use in the study of equilibria. A further drawback to using data obtained by the study of specific volume lies in the fact that the graphs connecting specific volume and composition are nearly straight lines, whether they deal with homogeneous or heterogeneous equilibria. Breaks in the graph will indicate the limits of the various phase fields, thus *Fig.* 5 represents the hypothetical specific volume-composition curve for an imaginary series in which a compound is formed. Such compounds have almost always a lower specific volume than that of their component metals, though in the case of those formed with either antimony or arsenic the reverse is true. It has been said that[1] deviation of more than 1 per cent from the mixture rule indicates the existence of compounds.

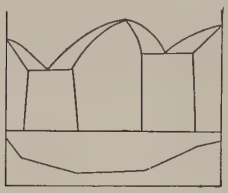


FIG. 5.

Fig. 6 shows some temperature-expansion curves for iron and iron carbon alloys obtained by Honda.[2] The first curve, which is that of pure iron, shows the allotropic modification

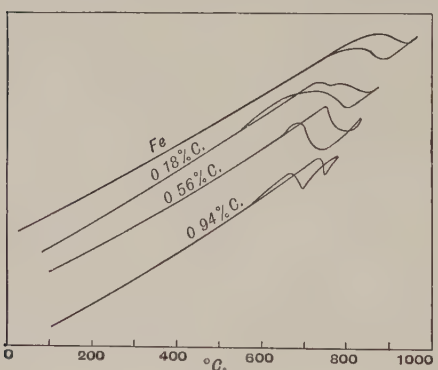


FIG. 6.

known as A3, both on heating and cooling. The second curve represents the expansion on heating and cooling of steel containing 0·18 per cent C. The change in expansion due to the separation of carbide can be seen on this curve in addition to the A3 point. In the other two curves the two points are merged into one (*vide* article on "Iron-carbon Alloys," § (7)).

§ (6) SPECIFIC HEAT.—Very little work has been done on the relationship between the constitution and specific heats of a series of alloys. The method has been used chiefly in searching for inter-metallic compounds, which in general appear to have a specific heat lower than that calculated from the law of mixtures.

§ (7) ELECTROLYTIC POTENTIAL.—The measurement of the electrolytic potential generated between an alloy and a pure metal when they are made the poles of an electrolytic cell, was one of the earliest methods used in the investigation of the constitution of alloy systems, Laurie[3] having carried out work on copper-tin alloys as early as 1888. The method has also been used with considerable success in the study of allotropic modifications in pure metals.

The study of electrolytic potential and the interpretation of the results obtained are beset with difficulties, some of them theoretical and others practical. The practical difficulties are many. In the first place it must be remembered that the action takes place at the surface of the metal. This means that the surface must be absolutely free from strain, oxide films, etc. Further, the potential generated will vary with the constituents exposed to the electrolyte, so that in the case of an alloy which is not homogeneous, or one in which one constituent is sheathed by another, particularly when this latter is insoluble, very misleading results may be obtained.

Another practical difficulty is to decide what value to take for the electrolytic potential. When the alloy is first immersed in the electrolyte, a certain value is obtained, but this changes rapidly, generally in the diminishing direction. It may become asymptotic to a constant value or may even become reversed. Some observers have used data obtained from the E.M.F. generated at the first immersion, while others have used the final values. Neither method is entirely satisfactory.

The theoretical difficulties are mainly due to the fact that the theory of equilibrium between an alloy and an electrolyte is only known in the simplest cases. It has, for example, been assumed[4] that an intermetallic compound sends out ions of the same composition as the compound. This assumption appears to be quite unjustified in many cases.

The forms of E.M.F. composition curves to be expected in alloy systems have been summarised by Desch[5] as follows:

(i.) All the alloys of the series consist of conglomerates of pure metals. The potential

[1] Guia, *Chemical Combination among Metal*, p. 57.
[2] Honda, *Science Reports*, Tôhoku Imperial Univ. vi. No. 4.
[3] Laurie, *Trans. Chem. Soc.*, 1888. liii. 104.
[4] Reinders, *Zeit. f. phys. Chem.*, 1903, xlii. 225.
[5] Desch, *Metallography*, 2nd edition, p. 184.

throughout is that of the more positive metal, and the curve is a horizontal straight line.

(ii.) The metals form a continuous series of solid solutions. The potential varies in a continuous manner, and the curve has a logarithmic form.

(iii.) Solid solutions of limited concentration are formed. The curve is smooth within the region of solid solutions, as in (ii.); the gap in the series is represented by a horizontal portion of the curve.

(iv.) A single compound is formed, solid solutions being absent. The curve is composed of two horizontal portions connected by a vertical line representing a sudden change of potential.

(v.) Several intermetallic compounds occur in the series, but solid solutions are absent. The curve is composed of several steps like those of (iv.).

(vi.) Both compounds and solid solutions are formed. The curve is a combination of (iv.) or (v.) with (iii.). A vertical line, that is a sudden fall of potential at a certain composition, indicates the existence of a compound having exactly that composition. If two horizontal portions are connected by smooth curves, and not by vertical lines, the beginning and ending of these sloping portions indicate the appearance of new phases. If a compound forms solid solutions with both components, there is no sudden fall of potential, and the composition of the compound cannot be inferred directly from the curve.

In the measurement of electrolytic potential the electrodes used are generally the alloy being investigated and one of the component metals, and the electrolyte is an acid or alkali which forms a but slightly soluble salt with the positive metal.

Where the method is being used in investigating allotropic changes in pure metals, the difficulties are not so great. Generally speaking, one electrode will consist of a sample of thoroughly annealed metal which may even be amalgamated, while the other electrode is an annealed and quenched sample of the metal. The electrolyte will be a solution of a salt of the metal under investigation.

In all cases the E.M.F. is measured with a potentiometer or electrometer, so as to avoid polarisation.

Fig. 7 shows the E.M.F. of samples of pure zinc quenched at different temperatures.[1] The changes in the direction of the curve at the two allotropic change points are well marked.

§ (8) Magnetic Properties.—While the vast majority of metals and alloys are so slightly magnetic that no information can be obtained as to their constitution from magnetic measurements, yet in the so-called ferro-magnetic metals and their alloys these measurements have been much used.

The chief properties which have been investigated are the susceptibility, permeability, induction, coercive force, and remanence. In the study of magnetic properties as a means of investigating constitution the susceptibility, and particularly its variation with temperature, has been chiefly studied.

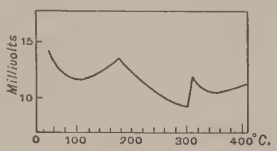


Fig. 7.

The shape of the susceptibility temperature curve varies according to the field strength; thus in the case of pure iron the curve in *Fig.* 8, which was taken with a field of H = 10, shows a steady rise of susceptibility till a temperature of 750° C. is reached, when the curve drops rapidly to zero at 790° C. With very high field strengths, on the other hand, the susceptibility falls at first slowly and then more rapidly; the temperature at which it becomes zero is, however, independent of the field strength.

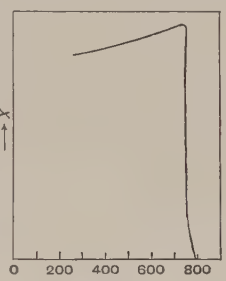


Fig. 8.

The study of variation of susceptibility with temperature has been much used in investigating the allotropic modifications of iron and its alloys. α iron is strongly magnetic, while β and γ iron are non-magnetic. Susceptibility measurements are therefore very suitable for determining the temperature at which the change takes place. In addition, cementite, Fe_3C, is magnetic up to about 200° C., and then becomes non-magnetic, due doubtless to a polymorphic change. This is the *Ao* point[2] which can be seen on all susceptibility-temperature curves of steels containing free cementite. A similar polymorphic transformation has been recently observed in the compound Fe_3P, which becomes magnetic on cooling at about 600° C. In neither of these cases can the transformations be detected by thermal or microscopical analysis. *Fig.* 8A, taken from Professor S. W. J. Smith's paper,[3] indicates the results obtained with cementite.

It would appear that these two compounds are amongst the few exceptions to what

[1] Bingham, *Institute of Metals Journal*, 1920, xxiii. 333.

[2] Honda, *Science Reports*, Tôhoku Imperial Univ. v. No. 5, 285.

[3] Smith, *Proc. Phys. Soc.*, 1912, xxv. 77.

seems to be an almost universal rule, that intermetallic compounds, *one* of whose components is a ferro-magnetic metal, are non-magnetic.[1] In the case of alloys, both of

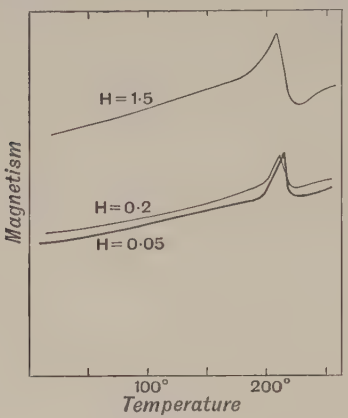


FIG. 8A.

whose components are ferro-magnetic, no compounds are formed, with the very doubtfully possible case of iron and nickel.

Solid solutions consisting principally of a ferro-magnetic element are ferro-magnetic, but their compounds are para-magnetic.

While ferro-magnetic substances generally give rise to non-magnetic compounds with non-magnetic elements, it has been found that in certain cases ferro-magnetic compounds are formed from non-magnetic substances. The most important of these are the Heusler alloys.[2] These are essentially alloys of copper and manganese containing either aluminium, tin, bismuth, or certain other metals. The best results are obtained when aluminium is used. It appears certain that these magnetic properties are connected with the formation of compounds, and in the case of the Cu-Mn-Al alloys the ferro-magnetic material appears to be a solution of Cu_3Al and Mn_2Al; these two compounds are themselves very slightly magnetic. The constitution of the series has not been properly worked out, but it is obviously very complex, and it has been found that thermal treatment has a marked effect on the magnetic properties of the alloys.

Other intermetallic compounds are known to be ferro-magnetic. Amongst the more interesting of these are the compounds of manganese with bismuth, boron, and antimony. The first of these, MnBi, is especially interesting in view of the fact that bismuth is diamagnetic. The compounds Mn_2Sb, MnSb, and MnB have a coercive force greater than that of tungsten steel.

Magnetic measurements have been used in studying the constitution of alloys of tin and aluminium with some of the ferro-magnetic elements. Thus *Fig.* 9 [3] represents the sus-

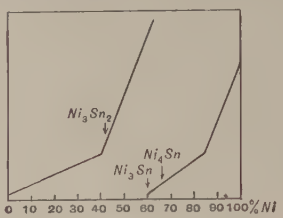


FIG. 9.

ceptibility temperature curve of the alloys of tin and nickel, the composition of the compounds being indicated on the curve. Up to 60 per cent Ni the observations were carried out at 25° C., above this at 550° C.

§ (9) HARDNESS.—The study of the hardness of alloys has been carried out more with a view to investigating their commercial usefulness than as a means of throwing light on their constitution. Much can be learned from this property, however, from this latter point of view.

It is probable that under the term hardness are comprised several different properties, as various methods of measurement do not always give concordant results.

In heterogeneous fields the curve connecting hardness and composition approaches a straight line joining the hardnesses of the component metals. Where solid solutions are formed the hardness curve rises between the components and reaches a maximum at a

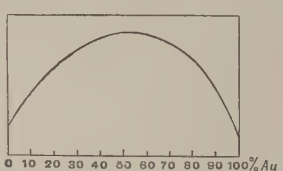


FIG. 10.

composition approximating to that of equal weights of the components. When a compound is formed it is generally much harder than its component metals, though if it forms solid solutions with both components the composition of the compound will be indicated by a minimum on the hardness curve. An example of the second case (*i.e.* where solid solutions are formed) is shown in *Fig.* 10, which

[1] It must be admitted, however, that carbon and phosphorus not being metals, these two compounds are not, strictly speaking, intermetallic.

[2] Heusler, *Verh. Deut. Phys. Gesellschaft*, 1903, p. 219.

[3] Honda, *Ann. de physik*, 1910, xxxii. 1003.

represents the hardness of the gold-silver alloys.[1] To illustrate a more complicated case reference may be made to the hardness of the copper-tin alloys. The curve shown in *Fig.* 11 is replotted from results obtained by Haughton and Turner [2] and represents the hardness of alloys containing up to 50 per cent of tin. Beyond this point the alloys were too far removed from equilibrium for their hardness to be correlated with the constitution. Up to 10 per cent Sn the curve is nearly a straight line corresponding to the α solid solution. Between 10 per cent and 25 per cent Sn there are two phases present, α and the compound Cu_4Sn, and the hardness curve is a rapidly rising straight line. From 25 per cent to 32 per cent Sn the alloys consist of

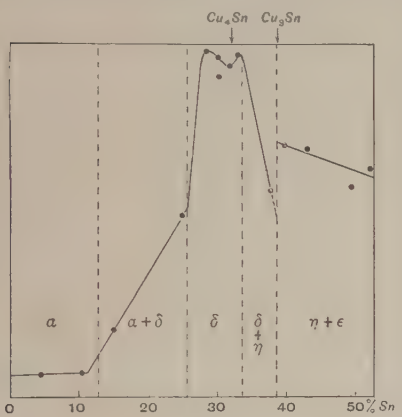


FIG. 11.

solid solutions of Cu_4Sn. The hardness rises rapidly, then falls to a small minimum and rises again, the minimum corresponding with the composition of the compound. Between 32 per cent and about 38 per cent Sn the hardness falls in a linear manner corresponding to the heterogeneous field of Cu_4Sn and Cu_3Sn. It then rises steeply at 38 per cent Sn, which, in the published diagrams, is shown to be insoluble in either of its neighbours, and then falls once more along a straight line in the field $Cu_3Sn + \epsilon$.

§ (10) THE HALL AND THE NERNST EFFECTS.—Both these effects have been studied to a limited extent in America in connection with the constitution of alloys. It would appear that the curves are very similar to those connecting thermal E.M.F. and constitution. *Fig.* 12 shows the Hall and the Nernst effects in the antimony-zinc alloys.[3] It will be seen that in both effects the existence of the compound SbZn is marked by a very large

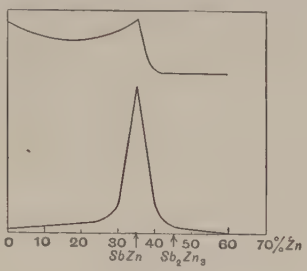


FIG. 12.

peak in the curve, but that the compound Sb_2Zn_3 is not shown.

§ (11) PHOTO-ELECTRIC AND OPTICAL PROPERTIES.—The element selenium is the best known of the metals exhibiting marked photo-electric properties. Its electrical resistance is considerably reduced by the action of light. It has recently been shown [4] that a thallium oxygen sulphur compound behaves in a similar way, the photo-electric effect being even more marked than with selenium. Very little systematic study of the relationship of photo-electric effects and constitution has been carried out, and it cannot be claimed that, in the few cases that have been investigated, much light has been thrown on the constitution by the work.

The optical properties have been even less studied, and in the few cases investigated correlation with the constitution is very difficult. *Fig.* 13 shows the index of reflection of the silver-copper series,[5] the phase

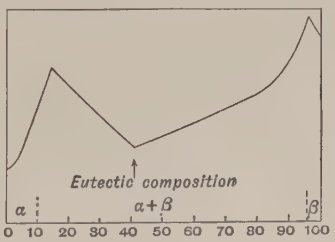


FIG. 13.

fields being indicated on the base line of the diagram. It will be seen that the index of reflection rises with increasing saturation of the solid solution and then falls on the appearance of a second constituent, reaching a minimum at the eutectic composition. It seems unlikely that this method has any advantage over microscopic study as a means of *investigating* constitution. J. L. H.

[1] Kurnakoff, Pushin, and Semkowski, *Zeit. anorg. Chem.*, 1920, lxiii. 123.
[2] Haughton and Turner, *Inst. of Metals Journal*, 1911, vi. 92.
[3] Smith, *Physical Review*, 1911, xxxii. 178.
[4] W. Case, *Phys. Rev.*, April 1920, p. 289.
[5] Oppitz, *P.R.*, 1917, x. 156.

ALLOYS, SOME SPECIAL

Under the present heading those alloys are dealt with which are of special importance or interest either from the point of view of their physical properties or on account of their utility for particular purposes in the laboratory, either for the construction of instruments or otherwise. The alloys most commonly met with, such as ordinary brass and bronze, steel, etc., will only be referred to as far as necessary for purposes of comparison.

§ (1) Special Bronzes and Brasses.—The simple alloys of copper with either zinc or tin are dealt with elsewhere,[1] but there are a whole class of materials, sometimes termed "special" brasses or bronzes, in which the properties of the simple alloys have been modified in various ways by the introduction of other metals or metalloids.

(i.) *Manganese Bronze.*—One of the best-known of these is so-called "Manganese Bronze." As a rule this is merely a brass (alloy of zinc with copper) in which varying proportions of manganese and of some other metals have been incorporated. The percentage of manganese is never very high, and sometimes this metal is almost entirely absent. Properly, such material should be described as "Manganese Brass."[2] Alloys of this type are used for the sake of the very considerably greater strength and hardness which the presence of the added elements confers upon them. Other "special" alloys derived from the ordinary copper alloys are Phosphor Bronze and Lead Brass.

(ii.) *Phosphor Bronze.*—Phosphor bronze is made and used in a variety of grades, the proportion of phosphorus present varying from zero up to 0·9 per cent. Those alloys of this type in which the phosphorus content of the finished alloy is small owe their special value to the fact that a certain amount of phosphorus has been employed in their production. This element is generally introduced into the alloy while molten in the form of an alloy of tin and phosphorus. The metalloid has a very strong affinity for oxygen, and reduces any oxide of tin which may be present in the metal. In many instances the quantity of phosphorus introduced is carefully adjusted so as to be just sufficient entirely to de-oxidise the alloy, and in that case no phosphorus or the merest trace can subsequently be found by the chemical analysis of the finished material. The bronze thus treated is none the less very much superior to a similar alloy from which the oxide has not been removed, and to that extent justifies the name "Phosphor Bronze." This material is often used for castings in which special soundness and strength are required, although in regard to actual strength other alloys can be found which give higher values. If phosphorus remains in the metal when cast, it gives rise to the presence in the alloy of a hard structural constituent, phosphide of copper. The presence of this constituent leads to a very material hardening and stiffening of the metal, accompanied by a marked reduction in ductility. A phosphorus content of 0·4 per cent renders the alloy too hard to be rolled or forged. On the other hand, the combined hardness due to the copper phosphide and the toughness of the bronze matrix of such a material renders it suitable—when the phosphorus content is high enough—to serve as a "bearing metal," *i.e.* as a lining for bearings of shafts or other moving parts, since it has been found that the desirable structure for an alloy in such a service is that of a very hard and generally brittle constituent embedded in a softer and tougher matrix. Other bearing-metal alloys are mentioned below.

(iii.) *Lead Brass.*—Lead is frequently added to copper alloys intentionally, although in small quantities it is generally present as an impurity derived from the zinc employed in the manufacture. Lead does not appear to enter into these alloys as a normal constituent which can crystallise from liquid solution, but rather to remain in the liquid alloy in the form of a fine emulsion. When the alloy has solidified the lead is found scattered through it as fine globules. Its effect on the physical and chemical behaviour of the alloys is, none the less, very marked. From the physical point of view the most pronounced effect is that it renders the alloys very much easier to treat in rapid-cutting machine tools. For use in automatic machines and where rapid production of a finely finished surface is required, brasses containing up to 3 per cent of lead present very great advantages, although the strength and toughness are appreciably diminished. The precise manner in which lead produces this effect has not, perhaps, been demonstrated, but the action probably consists in rendering the metal sufficiently brittle to allow the cuttings produced in the machine tool to break off short instead of forming long and tough coils, while at the same time the dragging effect on the cutting tool is reduced.

(iv.) *Copper-aluminium Alloys.*—Among the alloys possessing the greatest strength attainable in non-ferrous materials, and at the same time possessing a series of other valuable properties, those of aluminium with copper, containing between 89 and 97 per cent of copper, are the most remarkable. Among the

[1] See "Alloy Systems, Typical," § (2), etc.
[2] Report of the Committee on the Nomenclature of Alloys, *Journ. Inst. Metals*, 1914, vol. xi. No. 1.

outstanding features of this group of alloys are great strength (tensile tests exceeding 50 tons per square inch can be obtained), great resistance to corrosion, and the power of withstanding prolonged exposure to relatively high temperatures.[1] This group must, of course, be regarded as including the more complex alloys containing either manganese, iron, or nickel in addition to aluminium, the latter elements, however, being present in smaller proportions than aluminium itself. Perhaps the group containing from 1 to 2 per cent of iron are the most important. These lend themselves very well to the process known as "die casting," in which the molten alloy is poured into a metal mould of accurate shape and size. After solidification the casting is sufficiently accurate to be employed for many purposes without further treatment such as machining The strength and hardness of these alloys can, of course, be varied over a wide range by varying the amount of aluminium present. Thus an alloy consisting of approximately 10 per cent of aluminium and 90 per cent copper has physical properties closely resembling those of a mild carbon steel. If the aluminium content is much lower, on the other hand, extremely tough and ductile metal can be obtained which can undergo very drastic treatment either hot or cold. Two features of these alloys, however, require mention, since they tend to limit their usefulness. The first is the difficulty which is encountered when the attempt is made to solder them with ordinary tinman's solder. It is generally possible to "tin" a fresh-cut surface of one of these alloys a first time, but any subsequent effort to re-tin or re-solder the same surface meets with failure. The alloy apparently oxidises slightly under or through the layer of tin, with the result that the latter tends to peel off. It is probable that the use of special solders, similar to those employed in soldering aluminium, might overcome this difficulty, which, in itself, would constitute a serious disadvantage in the use of these alloys for certain types of instrument. A second disadvantage is a certain difficulty in satisfactorily machining these alloys. Cutting tools tend to "chatter" on them and to leave the surfaces with a peculiar wave-form marking. This defect can also be overcome by the special adaptation of the cutting processes, but it is liable to cause difficulties and to raise prejudice against the use of otherwise very valuable materials.

Apart from the alloys already mentioned, a considerable number of "special bronzes" are made and sold under a variety of proprietary names. These alloys are, as a rule, very complex, and their constitution and structure are little understood. It is, further, very doubtful whether there is any advantage in this complexity, equal results being in many cases obtainable in simpler and more satisfactory ways. The influence of "added elements" on brass and bronze alloys, however, has not yet been as fully studied as it deserves. Thus the strengthening effect of iron on certain bronzes (some of which are well known under the name "Delta Metal") is recognised, but this, also, has not been systematically studied, although individual manufacturers may possess important information with regard to it. The influence of the "rarer" metals on copper alloys — as, for instance, tungsten, molybdenum, tantalum, etc.—appears to be entirely unknown.

(v.) *Copper-nickel Alloys.* — Better known, and of very considerable importance, are the alloys of copper with nickel, either alone or in combination with other metals, particularly zinc. The alloys usually known as "Cupro-nickel" range in nickel content from 15 to 20 per cent, the latter being the composition of the alloy extensively used for rifle-bullet mantles. This material, which is almost white in colour, is remarkable for its resistance to ordinary atmospheric corrosion, and it also resists moisture to a considerable extent. It is, further, remarkably ductile when properly made and treated, and is valuable particularly because it can be subjected to a very large amount of plastic deformation (cold work), even without annealing, without becoming unduly hard and brittle. Alloys of copper and nickel richer in nickel have also been used for various special purposes which justify the relatively high price due to the high cost of the nickel and the high temperature required for melting and casting such materials. An interesting alloy of this type, which is finding extensive practical application for purposes where a combination of great strength with resistance to corrosion is required, is known as Monel Metal. This alloy contains 67 per cent of nickel with 29 per cent of copper, together with about 4 per cent of iron and other impurities. It is described as a "natural" alloy, being produced direct from an ore containing copper and nickel in corresponding proportions. The production of the alloy in this way avoids the high cost of the separation and purification of the nickel and the cost of re-melting it. The further claim is made that the alloy produced in this "natural" way is superior to a material of the same composition produced synthetically. Similar claims have frequently been put forward in regard to other alloys, but have never been substantiated, and all the knowledge of alloys and their structure and constitution which has been gained during the last thirty years suggests most strongly that such a

[1] Eighth Report to the Alloys Research Committee, *Journ. Inst. Mech. Eng.*, 1906.

claim is not likely to have any foundation in fact.

(vi.) *Nickel Brasses.*—The alloys of copper, zinc, and nickel, already referred to, constitute a group of materials very widely employed in the production of table-ware and similar articles. They possess a fine white colour, very considerable resistance to corrosion, very great ductility, which readily allows of forming them by pressing or stamping into almost any desired shape, and they form a particularly satisfactory basis for electro-plating with silver. These materials were formerly known as "German Silver," but recently the somewhat misleading name of "Nickel Silver" has been substituted. According to the systematic nomenclature of the Institute of Metals [1] they should be termed "Nickel Brass."

§ (2) Resistance Alloys.—In regard to nickel and its alloys, reference must be made to a group of materials [2] intended to resist the effects of prolonged exposure to high temperatures—frequently in the form of electrically heated resisters. The development of the electrically heated resistance furnace for laboratory or small industrial uses soon created a demand for a material which could serve as a substitute for the expensive and sensitive platinum which was originally employed as the winding. The first effort in this direction consisted in the use of pure nickel wire, but this had many disadvantages. In the first place, being a pure metal, it has a high temperature coefficient of electrical resistance, and a much higher voltage was required when the furnace was hot than when it was first connected; this entailed the provision of heavy regulating resistances and constant attention during the heating-up process. Further, nickel itself not only became oxidised somewhat rapidly, but also underwent a process of disintegration or embrittlement which generally ended by the rupture of the winding. Once broken in a single place, such a winding could not be repaired but had to be entirely replaced.

At the present time a series of special alloys, which have mainly been developed in America, are available for this purpose; they still leave much to be desired, particularly in regard to their life when the furnace is required to work at any temperature above 1000° C., but up to that temperature they are eminently satisfactory. These are known under various proprietary names, such as "Nichrome," "Chromel," etc.; an English variety is known as "Chronic." These all contain nickel and chromium, iron or manganese or both being also present in varying proportions. The typical composition of "Nichrome" is as follows:

Nickel	58 to 62	per cent.
Chromium	8 to 14	„
Iron	23 to 24	„
Manganese	0·5 to 2	„

These heat-resisting alloys are also employed for a variety of purposes other than furnace windings. Thus Nichrome in the form of castings is now widely used for the construction of various types of plant, or parts of plant, which are exposed to prolonged heating. In this thicker cast form the material can withstand exposure to high temperatures for a very long time, and in many cases justifies its high cost as compared with iron. Case-hardening boxes and pyrometer sheaths are examples of such uses. Further, in the form of wires of various thickness, these nickel and nickel-chromium alloys are frequently made use of as base-metal thermocouples, and with care their use can now be extended up to temperatures as high as 800° C.

Efforts have recently been made to improve alloys of this type by the introduction of an element which should provide them with a tough, impermeable skin of oxide. It is such a skin of oxide which gives to the copper-aluminium alloys (rich in copper) their power of withstanding very prolonged heating without being "burnt," but in that group of alloys the utility is limited owing to the fact that they reach their melting-point near 1000° C. The introduction of aluminium into nickel or its alloys with chromium has been attempted, but unfortunately it has a very marked embrittling effect, owing to the formation of very hard and infusible but brittle intermetallic compounds. The presence of even a small amount of aluminium accordingly makes the alloys very hard and renders rolling or forging difficult if not impossible. Some little success has, however, been attained in the case of material which is either to be used in the form of castings or is only to undergo a small amount of subsequent working. Neither wire nor ribbon has yet been made of these alloys.

§ (3) Cutting Tools.—The combination of nickel with one of the rarer metals—zirconium—has also led to the evolution of another American alloy, known as "Cooperite," which is intended for use as a cutting tool in lathes and other machines. Little is known of this material in this country, although a somewhat similar material, known as "Stellite," has been extensively tried here for various purposes. This, like "Cooperite," is an extremely hard, non-ductile, and non-forgeable alloy which is cast into the approximate shape of the desired tool or object and is then finished by grinding. Stellite, which is an alloy containing (in one

[1] Report of the Committee on the Nomenclature of Alloys, *Journ. Inst. Metals*, 1914, vol. xi. No. 1.

[2] See "Resistance, Standards and Measurement of," § (4), Vol. II.; also "Thermocouples," § (2), Vol. I.

of its varieties) about 35 per cent of chromium, 55 per cent of cobalt, and 10 per cent of tungsten, is extremely hard but entirely non-ductile, and cannot be appreciably softened by any known means. When used as a cutting tool, it can be allowed to work considerably faster than the best of the "high speed" steels, since the higher temperature does not soften "Stellite." On the other hand, the alloy is distinctly weaker than steel and can only be used where the cutting operation is smooth and regular. For a "roughing cut," where the tool is exposed to shock at each revolution if the stock happens to be somewhat excentric in shape, "Stellite" tools are too brittle and liable to break away. From the physical point of view, Stellite is interesting as being one of the hardest of known metallic substances, while it is at the same time entirely non-magnetic. It can sometimes be used with very satisfactory results for pivots or knife-edges, particularly where magnetic materials are inadmissible. Such articles must, of course, be cast as nearly as possible to the required shape and finished by grinding.

§ (4) Tungsten, Molybdenum, and Tantalum.—Although not strictly "alloys," some mention should be made here of the remarkable properties of tungsten, molybdenum, and tantalum. Tungsten in particular is of special interest from the point of view of the physical laboratory, on account of its special physical properties. Its extremely high melting-point and great permanence at high temperatures are already fully utilised in the modern electric-lamp bulbs and in the thermionic valve, as well as in the use of the tungsten "target" in the Coolidge and other X-ray tubes. Even at ordinary temperatures, however, the material is remarkable. It possesses very high tensile strength and an exceptionally high modulus of elasticity (Young's modulus) combined with a very high density. With these it combines extreme indifference to the effect of chemical agencies; exposure to moist air has no greater effect upon it than on platinum, while it is also capable of resisting the majority of acids. One of the uses which has been suggested, and is now being tried, is for standard weights. It has been found that it is now possible to obtain the metal in masses of adequate size for smaller weights (up to one kilogramme at least) in perfectly sound form, quite free from flaws or cavities even when examined with the microscope in section. The properties of molybdenum and tantalum are less well known, but are in many respects similar to those of tungsten. Molybdenum is, however, a much more ductile material and therefore more tractable for many purposes. Tantalum, on the other hand, although workable, is capable of acquiring great hardness and can be made to take and keep a good edge. On account of its incorrodibility, its use has been suggested for surgical and dental instruments, but it would seem that modern chromium steels ("stainless") will meet the same requirements in an easier and much less expensive way.

§ (5) The Rare Earths.—Another group of comparatively rare metals are also finding a series of applications, principally in their alloys. These are the "rare earths," mainly Cerium. In the form of an alloy known as "Misch Metall" these metals are reduced from their ore—the well-known Monazite sand of Brazil. To form the pyrophoric metal used for the production of sparks in cigar-lighters and similar appliances, this "Misch Metall" is alloyed with a suitable proportion of iron. The commoner metals of the alkaline earths are also finding applications. This is particularly so in the case of calcium and barium. Some of the alloys of these metals with aluminium are proving useful for special purposes. Their alloys with lead, however, appear to be more important. The lead-barium alloy, particularly, is at the present time being exploited as a bearing-metal in America. Like the alkali metals (sodium, etc.), the alkaline earths have the power of increasing the hardness of lead to a very marked extent, the hardness increasing for some considerable time after the metal has been cast. The structure of the resulting material shows relatively hard and brittle crystals embedded in a soft lead matrix, thus providing the essential characteristics of a good bearing material. The purpose of introducing such new alloys for bearing purposes, however, appears to be mainly an economic one, with the object of avoiding the use of the expensive metal, tin, which forms the basis of the great majority of the bearing alloys hitherto employed. These have generally consisted of tin containing from 8 to 10 per cent of antimony together with from 3 to 5 per cent of copper.

§ (6) Solders.—Tin itself forms the basis of a series of important alloys. Its most widespread use is probably in ordinary tinman's solder, which is an alloy of tin and lead. The softest, most fusible solder is the eutectic alloy of lead and tin, containing approximately 63 per cent of tin. This is, however, needlessly expensive for most purposes, and the usual "best" solder is a mixture of lead and tin in equal proportions, while cheaper and less fusible solders often contain as much as 70 per cent of lead. Recently it has been suggested that such solders might with advantage be hardened by the introduction of a small percentage of antimony, and tests seem to indicate that an addition of 1 per cent of antimony at all events does not injure the solder. Tin also enters largely into the composition of solders designed for use with aluminium and its alloys.

This is a field upon which a very large amount of energy and inventiveness has been wasted, since an impression appears to exist that no successful solder for aluminium is yet known, and that if one were discovered it would prove of immense value. Actually, there does not appear to be any very great demand for an aluminium solder, although for certain repair purposes, particularly under war conditions, a reasonably satisfactory solder was desired—and obtained. Two main difficulties exist with regard to the soldering of aluminium. The first resides in the fact that all the more fusible alloys of aluminium appear to be much more readily attacked by all manner of chemical agencies than is pure aluminium or its more resistant (and less fusible) alloys. Consequently, all soldered joints in aluminium are liable to fail in the course of time through corrosion. Fortunately the behaviour of any given solder in this respect can be readily tested by suspending the joint in the steam-space above boiling distilled water. Steam condenses on the metal, and the hot water rapidly attacks the solder if it is at all liable to disintegration. Many joints fail in a few minutes under this test, but some of the later solders can resist it for more than 100 hours. Such a solder is not likely to fail rapidly in use unless it is directly exposed to corrosive liquids, such as sea-water, etc. The second difficulty is more serious, since it seems to be almost impossible to tell when a soldered joint in aluminium, even with the best of the solders, is really sound. A really sound joint gives very good results under a tensile test, but a considerable proportion, even when every care is taken by skilled workmen, is always unsound and weak. Curiously enough, in spite of the fact that a great number of inventors have attacked this problem, all those who have approached success have arrived at much the same result, viz. an alloy of zinc and tin to which a little aluminium may or may not be added. The proportions of tin and zinc vary widely—from 40 per cent to 60 per cent of zinc, but this does not make any very vital difference to the resulting joints.

§ (7) Fusible Alloys: Type Metal.—Tin also enters, in varying proportions, into another series of alloys. These are the type metals and fusible alloys. The former vary very widely in composition according to the purpose for which they are intended. The alloys used in the casting of "stereo" plates for rotary presses such as are used for rapid newspaper printing contain a large proportion of lead, the remainder being tin and antimony. Here ease of melting and casting, and sufficient fusibility to allow the metal to be cast in papier-maché moulds are essential, while hardness and the power of resisting wear, and even facility for taking a fine finish and reproducing the finer details of the mould, are less important. For high-class type employed for the finest printing, the power of reproducing every minute feature of the mould or "matrix" is most important, and as the same type is used repeatedly in different settings, power to resist wear is also essential. Higher proportions of tin and antimony are accordingly used, the lead content being reduced correspondingly.

The fusible alloys generally contain tin, lead, bismuth, and cadmium. They are, approximately at all events, of the nature of eutectic[1] alloys. The simple binary eutectic of the lead-tin system melts at 180° C., and in the ternary system lead-tin-bismuth there is a eutectic which melts at 96° C. The constitution of the quaternary system lead-tin-bismuth-cadmium has not yet been fully investigated, but several alloys melting at low temperatures have been found. Among these are the following:

Cadmium	10 per cent.
Lead	26·6 „
Tin	13·3 „
Bismuth	50·1 „

Freezing at 70° C.

Cadmium	15·4 per cent.
Lead	30·8 „
Tin	15·4 „
Bismuth	38·4 „

Freezes at 71° C.

Cadmium	12·5 per cent.
Lead	25·0 „
Tin	12·5 „
Bismuth	50·0 „

Freezes at 65° C.

Some of these alloys possess somewhat remarkable properties, undergoing obvious transformations after solidification. These make themselves felt by a rise of temperature if the alloy is held in the hand while cooling; there is also a marked change of appearance of the surface of the metal, and an expansion occurs which generally breaks any glass vessel in which the alloys may have been allowed to solidify. The field of these fusible metals has not, however, been at all fully explored, and it is more than possible not only that alloys of still lower melting-points may be obtainable, but also materials free from undesirable volume changes, and having thermal expansions which render them more readily useful for many purposes where joints in apparatus or other practical applications are required.

§ (8) Amalgams.—Falling into a class somewhat similar to that of the fusible alloys are the amalgams. In these, instead of employing mixtures of metals of low melting-points such as tin and bismuth, one of the constituent

[1] "Alloys, Constitution of the Equilibrium Diagram"; also "Alloy Systems, Typical," § (9).

metals—mercury—has so low a melting-point that even in the pure state it is liquid at the ordinary temperature. In these circumstances it might be anticipated that the resulting alloys or amalgams would be entirely liquid at the ordinary temperature unless they contained only small proportions of mercury. Actually, however, the freezing-point of pure mercury is not very greatly depressed by additions of other metals, the eutectic compositions lying very near the mercury ends of most of the binary alloy systems. On the other hand, most of the mercury alloy systems contain well-defined inter-metallic compounds whose freezing-points are in several cases relatively high. Thus while the freezing-points of mercury, sodium, and potassium are −38·8° C., 97·6° C., and 62·5° C. respectively, the compounds $NaHg_2$ and KHg_2 solidify at 346° C. and 279° C. respectively. Certain uses of amalgams, however, depend upon a property which at first sight appears very remarkable, although it is readily understood in the light of modern knowledge of the constitution and transformations of alloys. This is the property of being capable of assuming a soft, plastic state followed by setting into a very hard and strong condition. While in the soft, semi-liquid state the alloy is obviously in a meta-stable condition; in the course of time, by the formation of an inter-metallic compound and the absorption of any liquid metal which may be present while the alloy is soft, the material assumes its stable and hard form. The transformations in the amalgams are, however, unaccompanied by any serious volume changes, and this renders them available for such purposes as dental stoppings and similar purposes.

The great majority of amalgams are readily formed by the direct action of mercury upon the finely-divided metal with which it is to be alloyed; frequently the most convenient method is to prepare the metal by a process of chemical precipitation. For this purpose metallic mercury may in some cases be used, while in others sodium amalgam is first prepared and then employed as a reducing agent. Another convenient method is to employ the mercury as a cathode in an electrolytic cell and to deposit the other metal on this cathode by means of a suitable current. With many metals, notably with the precious metals and with zinc, tin, etc., amalgamation occurs with very great ease. In the case of aluminium, much greater difficulty is experienced, and amalgamation by direct action of mercury on the metal in massive form only occurs if the aluminium is severely scratched while covered with mercury. No doubt this behaviour is due to the fact that aluminium is coated with a thin film of oxide, even when freshly scratched during exposure to air. If, however, mercury has been brought into actual metallic contact with aluminium, a remarkable phenomenon follows on subsequent exposure to air. The presence of the mercury appears to prevent the formation of the normal protective coating, with the consequence that the amalgamated aluminium oxidises with amazing rapidity. The formation of alumina can be watched, as a layer several millimetres thick is formed in a few minutes, the rapid oxidation being accompanied by a notable rise of temperature. The alumina is formed in the shape of little threads or fibres which appear to grow outward from the amalgamated surface and may attain a length of a centimetre or more before the action ceases. It is a curious and hitherto unexplained fact, however, that this action occurs most freely in the purest kind of aluminium, the presence of other metals or even of silicon to the extent of more than 1 per cent being enough to inhibit it entirely. The phenomenon can be shown in a still more striking form by exposing a surface of pure aluminium to contact with a solution of a mercury salt, such as mercurous nitrate or mercuric chloride, for a short time. If the surface, after a brief exposure, is rinsed and lightly wiped dry, the formation of alumina occurs very vigorously.

W. R.

ALLOYS, interpretation of the diagram of a system. See "Alloys, Constitution of," § (1) (v.).
Measurable properties of a series. See *ibid.* § (2).
Physical properties of. See "Alloys, The Relationship of Structure and Physical Constants," § (1).
Reversible and irreversible. See "Invar and Elinvar," § (2).
Rich alloys containing large proportions of an added metal, used for introducing that metal into other (less rich) alloys. See "Metals, Thermal and Mechanical Treatment of," § (1).

ALUMINA. See "Refractories," § (51).

ALUMINIUM, effect of low temperatures on physical properties of. See "Steels, Special," § (4)A (ii.).
In steel. See *ibid.* § (18).
Production of. See "Furnaces, Electric," § (9).

ALUMINIUM AND ITS PREPARATION

ALUMINIUM, the light white metal of which the use is daily becoming more prevalent, though of recently dated history as a metal, has long been known through the medium of its salts, and is, in fact, the third most abundant element in the earth's crust.

Diligently sought for in the early years of the nineteenth century by Davy, it was first isolated in 1827 by Wöhler, who reduced aluminium chloride by potassium.

Wöhler only prepared small quantities, however, and these in a not very pure form, and subsequent progress was dependent on the genius of Sainte-Claire Deville, who, by substituting the cheaper metal, sodium, for potassium, and the more suitable sodium-aluminium chloride for aluminium chloride, made the process commercially possible.

By the modifications and improvements on Deville's process effected by Castner and Webster, the purely chemical process was carried to a high level of efficiency, but it could not compete against the electrical method, once the development of the dynamo made this relatively so cheap.

Although Deville had, in 1854, reduced aluminium chloride in the electric arc, and though there were several patents on the subject in the succeeding years, it was not until 1886-89, when the Cowles process was launched, that electricity was made use of industrially for the production of aluminium.

This process consisted in the reduction of alumina by carbon at the high temperatures available in the electric arc, but as aluminium liberated in such circumstances readily combines with carbon to form aluminium carbide, the Cowles Brothers confined themselves to the production of alloys, the aluminium being absorbed by iron or copper as it was liberated, thus preventing further reaction.

However, as pure aluminium was not available by the Cowles process, that devised independently by Hall and Héroult (1886–1889), once established, soon superseded it.

The Cowles process was entirely electrothermal; the Hall-Héroult process is both electrolytic and electrothermal.

Essentially the process consists in the electrolysis of alumina dissolved in molten cryolite, the oxygen liberated combining with the carbon of the anode, and the heat generated by the passage of the current sufficing to keep the electrolyte molten.

It is this Hall-Héroult process which, with modifications only in detail, has increased the world's yearly production of aluminium from 7000 tons in 1900 to almost 200,000 tons in 1919.

Although compounds of aluminium—clays, rocks, etc.—are so abundant in nature, yet the only raw materials used commercially for the production of the metal are bauxite, an impure hydrated oxide, and cryolite, a double sodium-aluminium fluoride, as up to the present it has not proved feasible to extract the oxide of aluminium cheaply enough from any available compound other than bauxite.

Cryolite, 6NaF, Al_2F_6, is found plentifully in Greenland and in the Ural, or a compound indistinguishable from the purified native product may be prepared artificially.

Bauxite, $Al(OH)_3$, containing as impurities iron oxide, titanium oxide, and silica, occurs extensively in France and many other parts of the world.

Alumina, (Al_2O_3), is the purified product derived from this.

The general method of purifying is that known as Baeyer's process, in which the bauxite is first crushed and calcined, and then digested under pressure with hot caustic soda solution. This results in the solution of the alumina as sodium aluminate, the impurities being left in suspension.

From these impurities the sodium aluminate is filtered by means of filter presses and transferred to precipitation tanks, where some recently precipitated alumina is stirred in. This has the interesting result of precipitating 70 per cent of the total alumina present, with the regeneration of an equivalent amount of caustic soda.

The hydrated alumina is now filtered off, washed, and heated to over 1000° C. to drive off all combined water. At this temperature it undergoes a molecular change, and becomes more dense and less liable to absorb moisture.

From these processes the alumina comes to the reduction factory in the form of a fine white powder, having a specific gravity of about 3·6 to 3·7, though its bulk density is under ·8.

Cryolite melts at 1000° C. to a clear colourless liquid and readily dissolves alumina, the addition of which in small quantity lowers the melting-point to about 915° C. The melting-point is also lowered by the addition of other salts such as calcium fluoride, or by the addition of aluminium fluoride, itself one of the constituents of cryolite. However, the addition of other salts to the fused cryolite has to be conducted with care, because, though a low melting-point is desirable, the volatility of the various ingredients and the density of the molten mixture have to be considered.

Electrolysis is effected in a rectangular furnace or tank of iron or steel plates, lined first with a layer of heat-insulating material, and then with a thick layer of carbon. This bath contains the molten electrolyte, the bottom of the bath and the molten aluminium which collects there forming the cathode, while a number of carbon rods or blocks suspended in the electrolyte form the anodes.

From the bottom of the bath electrical connection is made to the conductors running outside the furnace, by one of a number of devices, the objects of which are to secure as far as possible good electrical conductivity without too great heat loss.

Many different types and sizes of anodes and anode connections are in use. The anodes may be round or square in section, and may vary from 3 inches to 25 inches in diameter and from 10 inches to 36 inches in length. The anode connections may be of iron or copper, and may be pressed into the anode before baking, or screwed in subsequently.

The sides or walls of the furnace may be built of bricks of carbon, or be made of carbon mixture rammed or pressed into position.

In practice, the construction of a furnace is an operation requiring great skill and care, the subsequent life and efficiency of the furnace depending almost wholly upon this. The essential points are that the carbon sides shall not disintegrate or fall away; that both sides and bottom shall be as impervious as possible to metal or molten electrolyte; that the heat losses through the sides and bottom of the furnace shall not be too great; and that the current path is one of low resistance.

The size of the furnace or bath depends on the current for which it has been designed, the smallest type in current commercial use taking 8000 amperes, but though the many types of furnaces vary greatly in detail, yet they are all the same in principle.

FIG. 1.

Fig. 1 represents a longitudinal section of a typical furnace fitted with an iron plate cathode connection. The bath of such a furnace may measure about 5 feet in length and 2½ feet in breadth, the external dimensions varying with the thickness of lining. A number of such furnaces are always connected in series, the cathode of one being connected to the anode of the next in succession, and for convenience of manipulation they are generally arranged in long rows with sufficient working spaces in between.

At the British Aluminium Company's large hydro-electric works in Scotland the power is obtained from a large reservoir constructed in the surrounding hills at a height of 1000 feet above sea-level. The power for the plant of the Aluminium Corporation, Ltd., Wales, is also derived from lakes in the surrounding hills with a head of 1000 feet.

In both these cases the water is carried in steel pressure pipes to the turbines, which are of the Pelton Wheel type, with two water jets.

One set, consisting of a turbine and two shunt-wound generators arranged to operate in parallel, is allocated to a series of furnaces, the actual current taken and the pressure at which it is supplied depending, at any moment, on the number of furnaces in circuit, their resistances, and back E.M.F.

As each furnace requires a certain kilowatt-input to maintain its working temperature, and as both the theoretical metal yield and the voltage drop due to the resistances of cables, connections, and electrodes are proportional to the current, it is an interesting problem, which good practice is always endeavouring to solve for each type of furnace, to determine the distribution of power which will give the highest efficiency. The problem is complicated by the fact that the current efficiency falls off as the distance between the electrodes is unduly diminished.

The anode support is generally so arranged that all may be raised or lowered simultaneously, or that each may be adjusted separately. By regulating each individual anode or the distance between the electrodes in this way the operator is able to control the current distribution and the kilowatt-input into his furnace, by this latter determining its temperature.

Cryolite alone is a poor conductor, but when alumina is added the conductivity becomes, when measured by fused salt standards, very good. The actual conductivity value varies with temperature and composition, but is usually in the neighbourhood of 5 mhos per inch cubed. In fact, the solution of alumina in cryolite is analogous to that of a salt in water, the alumina being ionised in a similar way.

On electrolysis, aluminium is liberated at the cathode, while the oxygen ions arriving at the hot carbon anodes do not appear as oxygen, but on losing their charge combine with the carbon forming carbon dioxide and carbon monoxide. Thus the net result of the reaction is a reduction of alumina by carbon.

The decomposition voltage of alumina is generally stated from thermochemical considerations to be 2·8, but as the reaction takes place at an elevated temperature, and the action of the carbon at the anode has to be taken into account, this is evidently too high. The still higher voltage used in practice (6 to 7½ volts per furnace) is necessary, of course, to overcome the resistance of connections,

electrodes, and the bath itself, the requisite temperature being maintained by the heat furnished in this process.

As the anodes are consumed in the process, and the ash contained in them is deposited in the bath, appearing as impurity in the metal, it is important that their ash content be low, and that the ratio of carbon consumed to aluminium produced be kept low. Anodes are generally made of the purer varieties of coke, the cost of pure graphite being quite prohibitive.

The coke is calcined to get rid of volatile matter, and then crushed. The powder is mixed into a paste with hot tar and pitch, and this paste is moulded in hydraulic presses to the required shape. The moulded anodes are then removed to furnaces where they are baked for some days at a temperature which exceeds 1000° C. at its maximum. After fitting with connections, the anodes are ready for use in the aluminium reduction furnaces.

The finished anodes should be hard and resilient, of low porosity, and not too readily oxidisable in air. Their ash content should not exceed 3 per cent, preferably being under 1 per cent, and their electrical resistivity should not greatly exceed ·002 ohm per inch cubed.

Theoretically, the atomic weight of aluminium being 27, and it being trivalent, the passage of 1 faraday (96,540 coulombs) should liberate 9 grams of aluminium; or expressed in units which are more used in practice, the passage of 8000 amperes for one week should liberate 994 lbs. of aluminium. In practice, however, the theoretical yield is never attained.

In its simplest form, the reaction is

$$Al_2O_3 = 2Al + 3O,$$
$$102 = 54 + 48,$$

showing that the weight of alumina required is almost twice that of the aluminium produced. There must, therefore, be regular additions of alumina to the electrolyte to make up for that electrolysed. In practice, the change in resistance of the electrolyte accompanying the depletion of the alumina in the working zone is used to indicate the necessity for adding more alumina, voltmeters or lamps placed in shunt across the furnace terminals indicating by their increased reading or increased brilliancy when this is required.

In theory, there need be no consumption of cryolite, all the aluminium produced being obtained from the alumina, but in practice cryolite decomposes and volatilises to a slight extent, particularly at too high temperatures, and additions of fresh cryolite or aluminium fluoride have to be made from time to time to make up the deficiency.

The temperature control is almost automatic. With a well-designed furnace the rate of rise of metal on the bottom of the furnace is practically the same as that of the wastage of the carbon anodes. Thus the distance between the electrodes remains almost uniform from one tapping period to the next, and the necessary adjustments of the anodes are reduced to a minimum.

The whole process is one which goes quietly on from day to day, with no change other than that necessitated by the periodic additions of alumina, the changing of anodes as they are consumed, the tapping or ladling out of metal, the cutting out of circuit of old furnaces, and the putting in of new. To superficial observation the whole seems very simple, but the closer the study of the subject the more apparent are the fine margins on which successful working depends. For example, it is a necessity of the process that molten aluminium shall remain on the bottom of the furnace. Yet the specific gravity of the electrolyte at working temperatures may vary form 2·11 to 2·28, according to composition, while that of molten aluminium is about 2·30 at the same temperature. The narrow margin is obvious.

A furnace is generally tapped to remove the molten metal, or the metal is ladled out, once every two, three, or four days, according to convenience.

To secure a uniform product, and also to set free any electrolyte or other foreign matter which may be present, the metal is always remelted in a suitable furnace, which may be either gas-fired or electrically heated. In this furnace the metal is well stirred, and any foreign matter skimmed off.

Molten aluminium readily absorbs gases, particularly at high temperatures. It is therefore important that the temperature of the metal should not greatly exceed the fusion point. Electrically heated furnaces, which are capable of complete temperature control, are very suitable for this purpose, and as they have several other incidental advantages, they bid fair, shortly, to supplant gas-fired furnaces in this respect.

As the metal is cast from the remelting furnace it has generally a purity varying from 98 per cent to 99·6 per cent, the chief impurities being iron and silicon. Any considerable quantity of iron in aluminium is readily visible on a polished or fractured surface, the iron-aluminium compound which is formed being hard, white, and shining. Silicon in the metal is also said to be capable of detection by its slightly darker colour.

The metal is cast from the remelting furnace

in various forms, according to subsequent requirements, in notched bars for casting and the formation of alloys, and in ingots or slabs for rolling and extrusion.

Aluminium is marketed either in ingot form or in a variety of manufactured forms such as sheet, wire, rod, sections, etc. For rolling, ingots are first heated, and are then rolled down hot in a number of passes to sheet, which is then rolled cold to gauge. In this way foil as thin as ·0005 in. may be rolled, and in fact this may be beaten even further, almost to the fineness of gold leaf.

By hot rolling followed by cold drawing, tubes, rods, and wire may be made in the usual way, and by extrusion at from 400° C. to 600° C. continuous rods and a comprehensive variety of extruded sections may be produced. The Lewis Gun radiator is an interesting example of such extrusion.

Aluminium may also be spun, pressed, or stamped with ease into a variety of shapes; the cooking-utensils which are now so familiar being produced by the spinning of aluminium sheet.

The numerous applications of the metal in industry are dependent on its varied mechanical, electrical, and chemical properties. After its characteristic appearance, which is now so well known that to call it tin-white or silver-white no longer conveys any information, its most strikingly apparent property is its lightness. Its density, 2·70 at 0° C., only exceeds that of magnesium, glucinum, calcium, strontium, and the alkali metals, and is in marked contrast to that of the other common metals (zinc, 8·2; iron, 7·8; copper, 8·9; lead, 11·4). In malleability and ductility it is only inferior to gold, silver, and platinum, whilst its tensile strength is about half, its electrical conductivity about 60 per cent, and its thermal conductivity about 45 per cent that of copper. Its melting-point is given by the American Bureau of Standards as 658·7° C., other recent determinations varying within a few degrees of this.

Its specific heat at 0° C. is ·21, increasing to ·22 at 100° C. On its specific heat at higher temperatures the data existing are rather contradictory, much of this, no doubt, being due to the fact that its melting-point was for long taken as 625° C.

Latschenko [1] gives for the total heat required to heat aluminium from 0° C. to just under the melting-point, the value of 187 calories per gram, and for the latent heat of fusion 64 calories per gram, a value markedly lower than that commonly accepted (80 calories per gram).

In the following table the main properties of the metal are summarised.

[1] *Journ. Russ. Phys. Chem. Soc.* x. 56, p. 311.

PROPERTIES OF ALUMINIUM *

Chemical symbol	Al
Atomic weight	27
Valency	3
Position in electrochemical series	10
Electrolytic solution potential to normal solution of $AlCl_3$	1·015
Mobility of Aluminium ion (H=316)	3×49·2 †
Melting-point	658·7° C.
Boiling-point	1800° C.
Latent heat of fusion	64-80 cals.
Specific heat 0° C.	·2098
Specific heat mean 0°-658·7° C.	·284
Electrical resistivity at 0° C.	1·026 microhms per in.[3]
Temperature coefficient of electrical resistivity at 20° C.	·0039
Thermal conductivity at 18° C.	1·28 cals. per 1° C. per in.[3]
Modulus of elasticity at 17° C.	4000 tons per in.[2]
Tensile strength—	
Annealed	5·6-6·7 tons per in.[2]
Sandcast	5-6 tons per in.[2]
Chill cast	5·4-6·2 tons per in.[2]
Hard bars	12·5-15·6 tons per in.[2]
Ductility (Erichsen test)—	
Sheet ·0126 in. thick	5·5-7·5
Sheet ·0403 in. thick	8·0-9·5
Sheet ·1018 in. thick	11·0-12·5
Specific gravity at 0° C. annealed	2·702
Specific gravity at 0° C. cold worked	2·700
Specific gravity at 600° C.	2·565 ‡
Specific gravity at 660° C. (molten)	2·381 ‡
Specific gravity at 800° C.	2·343 ‡
Coefficient of linear expansion per 1° C. at 0° C.	·0000245
Coefficient of linear expansion per 1° C. at 600° C.	·00003150
Cubic expansion 0° C.-100° C.	·7 per cent
Cubic expansion 0° to just before melting	6·1 per cent
Cubic expansion 0° to just after melting	10·9 per cent

* Merica, *Chem. and Met. Eng.*, 1918, xix. No. 4.
† Heyrovsky, *Chem. Soc. J.*, 1920, cxvii. 11.
‡ Edwards and Moorman, *Chem. and Met. Eng.*, 1921, xxi. No. 2.

The most striking of the chemical properties of aluminium is its reaction with oxygen. Under proper conditions the two will unite vigorously, even explosively, the heat developed in the formation of alumina being very intense, whereas in daily use of the metal there is no indication of such extreme action. The latter effect is due to the fact that, on exposure to the air, aluminium becomes superficially oxidised, the film of oxide then protecting the metal from further oxidation.

The molecular heat of formation of alumina is 392,600 calories, a value greatly in excess

of that of the oxide of any other element, the heat of formation of iron oxide, Fe_2O_3, and carbon dioxide, CO_2, for example, being 196,000 calories and 97,200 calories respectively.

This is the basis of the Goldschmidt aluminothermic process, called briefly the "Thermit" process. When metallic aluminium, in the form of powder, and powdered ferric oxide are intimately mixed, and the reaction is started by, say, a burning magnesium ribbon, the iron oxide is reduced at the expense of the aluminium, and the heat generated is sufficient to raise the temperature of the whole to about 3000° C. This reaction furnishes a convenient means of welding masses of iron, and a similar reaction is used to prepare pure metals from their oxides. It is because of this great affinity for oxygen that the metal is not found native, and it is also because of this that efforts to reduce alumina by means of carbon are so unsuccessful commercially. The reduction does take place, in fact, at sufficiently high temperatures, particularly as in the Cowles process, when the aluminium produced is at once absorbed by iron or copper, or as in the experiments by Moissan and others, when aluminium carbide is formed simultaneously.

The interaction between aluminium and air, water, etc., depends very much on the physical condition of the metal. As a powder, an amalgam, or in fine foil, it will react with moist air or water under suitable conditions, as its place in the electrochemical series and its very high heat of combination with oxygen would indicate. The resistance offered by aluminium to the combined action of air and water is affected by the presence of impurities, in general, the purer the metal the less being the measure of corrosion. Though aluminium is so slightly acted on alone by water, yet in contact with another metal there is a decided action because of the difference of potential established between the two metals. For this reason rivets of aluminium only should be used in aluminium ware.

The corrosion which does take place in aluminium, in sea-water, or in the presence of certain salts is also due in part to the existence of local areas of different potential. Both aluminium itself and its alloys, some of which are readily corroded in fresh water, can be very thoroughly protected by the use of enamels or varnish paints even under the most severe conditions.

Aluminium is readily dissolved by hydrochloric and hydrofluoric acids, is only very slowly acted on by sulphuric acid, and is practically insoluble in nitric acid. It is also readily acted on by mercury salts and by the alkali hydroxides and carbonates. Aluminium cooking-vessels, therefore, should not be cleaned with soda or very alkaline soap.

Aluminium combines readily with the halogens, with silicon and boron, and less readily with carbon, nitrogen, phosphorus, and sulphur. Its indifference to sulphur and sulphur compounds is one of its most valuable properties, distinguishing it from copper and making it peculiarly suitable for electrical and other purposes in the vicinity of gas-works, coke ovens, etc.

The alloys of aluminium are many and varied and are becoming increasingly important in industry. Broadly, there are two useful classes: heavy alloys with under 20 per cent aluminium, and light alloys with over 50 per cent.

Of the former the most important is the so-called aluminium bronze, an aluminium-copper alloy containing up to 9 per cent aluminium, which properly alloyed has a tensile strength of 35-40 tons per square inch. This has many useful applications where strength and non-liability to corrosion are important, and as its colour resembles gold, it can be used for imitation jewellery. With the addition of manganese, this alloy has excellent shock-resisting qualities.

Of the latter, there are numerous varieties containing magnesium, copper, tin, nickel, and manganese. These may again be divided into two classes according as to whether they are designed for casting and forging, or for rolling and drawing.

For casting, aluminium alone is for many purposes too soft and weak mechanically, but for cooking-utensils and for similar applications where resistance to corrosion is important, pure aluminium is always used. For other purposes hardeners are added, the most common being zinc or copper. The former of these is the cheaper, and the resulting alloy is the easier to cast, but the latter gives generally better results. The addition of 1-2 per cent manganese further improves the copper alloy. An alloy containing about 14 per cent copper and 1 per cent manganese has a tensile strength of 9-11 tons per square inch and is used for aluminium pistons because it retains its strength at high temperatures. The successful casting of light alloys in complicated forms is very difficult, but most of the difficulties encountered have been overcome in recent years.

Of the alloys suitable for rolling and drawing there are the magnaliums, containing about 2 per cent of magnesium along with other metals, and a variety of others of which duralumin perhaps is the best known. Duralumin has a specific gravity of 2·8, and one analysis of the alloy is as follows: Al, 94·2; Cu, 3·9; Mn, ·75; Mg, ·69; Fe, ·35; Si, ·11. Such an alloy heated to 400-450° C. and quenched in alcohol does not harden at once like steel, but only gradually, reaching its final value in twenty-four hours. Before treatment the tensile strength of the alloy may be 16 tons

per square inch with 14 per cent elongation, and, after treatment, become 25-30 tons per square inch with 19 per cent elongation.

Though there has been marked progress in the development of light alloys in recent years, there is yet much to be done, and a promising field for research in this direction lies open.

From the interesting properties of aluminium and the extensive variety of its alloys indicated above, the rapid growth of the metal's use in industry will be understood.

Taking first its use for electrical purposes, a comparison between it and copper is immediately necessary. As the conductivity of aluminium is 60 per cent that of copper, the ratio of the cross-sections of the metals for equal resistance is Aluminium : Copper = 100 : 60, but as the density of aluminium is 2·70 while that of copper is 8·89, the ratio of the weights of the metals for equal resistance is Aluminium : Copper = $100 \times 2{\cdot}70 : 60 \times 8{\cdot}89$. This is equal to 270 : 533·4 or 1 to 1·976. It therefore follows that for equal weights the conductivity of aluminium is almost twice that of copper, and that at any price under twice that of copper, the former is the more economical conductor.

The above is the main factor that determines the use of the one metal or the other for electrical purposes, but there are others which operate in certain cases. For example, in busbars where permissible temperature rise rather than voltage drop governs the cross-section of conductors, aluminium has a decided advantage, as its larger section admits of better radiation, while in wiring systems where there are frequent tappings and joints, copper easily holds its place. The jointing of aluminium cables for long gave trouble, because of the persistent layer of oxide which forms on the surface of the metal, but now there are several satisfactory jointing devices on the market, and where butt-welding can be resorted to, as with rods and bars, the joint is both mechanically and electrically perfect. Experience has shown that aluminium can be soldered, and soldered efficiently, but the joint is liable to electrolytic corrosion unless it is efficiently protected from atmospheric influences, and generally it is better to resort to other means available. One such process is the butt-welding referred to above, where the two ends to be welded are simply heated in a blowpipe flame and pressed together either by hand or mechanically, the collar of metal and oxide which is forced out being subsequently filed or cut off.

The resistance which aluminium offers to the action of sulphur and its compounds is a decided point in its favour. It is suitable for use in chemical works, gas-works, etc., and in insulated cables where bitumen and rubber are used the expensive tinning or winding with sulphur-free rubber, which is necessary in the case of copper, can be dispensed with.

Aluminium has proved highly successful for high-tension transmission work—it is now in use for tensions of 150,000 volts and for distances of 400 miles. Its larger section gives it a relatively smaller corona loss than copper, or alternatively permits a higher working voltage, while the strain on the insulation is also smaller with the greater cross-section. Aluminium cables require wider spacing between wires than copper, as their sag between supports and consequent liability to swing together is greater, but this is compensated for by the fact that the smaller weight of wire allows wider spacing or lighter structures.

The layer of oxide which is generally the cause of so much trouble in electrical work has also been turned to good account. When this layer has been strengthened by immersion of the wire in caustic soda or other suitable salt, it is even found practicable to wind coils with bare aluminium wire, insulated only between layers. These coils stand a higher working temperature than ordinary rubber insulated copper coils, are considerably lighter, and are unaffected by moisture. They have a fairly extensive use as field coils for traction motors and for the windings of lifting magnets.

Coming now to the uses of aluminium which are of more immediate concern to the average man, the most apparent is the rapidly increasing supply of cooking-utensils made of the metal. For culinary purposes aluminium not only looks clean, and keeps clean, but *is* clean chemically. Its salts are colourless and non-poisonous; it is not affected by organic acids; it heats rapidly, and it is light to handle. It is used to advantage in the paint and varnish industries, in the soap and candle industries, and in brewing. For these purposes large vessels of the metal are built up by means of autogenous welding. In this process, by the use of an oxy-acetylene flame and a suitable flux, two surfaces may be made to flow together and a seamless, smooth surface remain. A process which has been used for the repair of articles made of cast aluminium is cast welding. In this the work to be repaired is secured in a prepared mould and molten aluminium is run into and over the joint until the whole fuses together.

For decorative articles, and fittings of all sorts, for panelling of railway carriages, for the upper structures of ships, for parts of aeroplanes, motor cars, and cycles, and for the complete structure of lighter-than-air craft—the uses of aluminium and its alloys are legion. Its advantages in this direction depend on its lightness coupled with strength, freedom from corrosion and danger of fire, and good

appearance without continued applications of paint or enamel.

Automobile pistons and cylinders of cast aluminium alloy have proved markedly successful, not only from their lightness, but also from the high thermal conductivity of the metal, and great progress in this direction is certain in the future.

The use of aluminium in the thermit reaction has already been alluded to. By means of this reaction, cobalt, chromium, manganese, molybdenum, all of surpassing importance, can be obtained from their oxides, or alloys such as ferro-titanium may be prepared. A similar application of aluminium is its use in the steel industry for deoxidising and for keeping the melt warm in the ladle. Aluminium added in this way tends to prevent the formation of blowholes, and gives a higher density and better quality of steel.

One of the most important uses of aluminium during the war was for the production of ammonal, the main constituent of the well-known Mills Grenade, and one of the most convenient of high explosives. Ammonal consists of aluminium in the form of a fine powder intimately mixed with ammonium nitrate in proportions which vary according to the action desired. The uses of ammonal are not confined to war purposes, however, as it is an excellent blasting agent in mines and confined spaces, the products of its combustion being entirely harmless.

It has only been possible in the above to touch on a few of the many important applications of aluminium. Numerous extensions in the use of the metal will readily occur to the reader, and, marked as has been the progress in the development of the metal in recent years, it is safe to prophesy that with the progress of research, still more marked developments await it in the future.

D. F.

Brief reference may be made to the bibliography of the subject. Of detailed writing on the reduction process as it stands at present, there is none. The fullest account appears in *L'Industrie de l'aluminium*, Flusin (Legendre, Lyon), 1912. Professor J. W. Richards's *Aluminium* is the classic on the history of the metal, while Mortimer's *Aluminium* (Pitman) is an excellent little book on its manufacture, manipulation, and marketing. In a series of articles by Paul D. Merica in *Chemical and Metallurgical Engineering*, New York, 1918, August–December, there is a complete reference to all the published work on the metal, the properties of the metal and its light alloys are discussed, and full tables of physical and chemical data are given.

ALUMINIUM ALLOYS

Among the special alloys which are of interest from the physical point of view, particular importance attaches to those which may be grouped together as "Light" metals or alloys. Among these, aluminium and its alloys are as yet by far the most important, but attention is now being directed in an increasing measure to other light metals. Among these must be included magnesium, calcium, and beryllium or glucinum, and even silicon. Magnesium is already a relatively cheap commercial material, while calcium is also obtainable in the market. Of beryllium very little is known as yet, and it is not an industrial product, although investigations regarding it are in progress in several quarters. Silicon as a basis-metal for light alloys has not yet received much attention, probably because the relatively impure forms of metallic silicon which are ordinarily obtainable appear to be very brittle. As an alloying element in aluminium, however, it has assumed some practical importance.

§ (1) Aluminium.—Pure aluminium is a very soft and ductile but relatively very weak material. In the cast form its tensile strength does not greatly exceed 5 tons per square inch. In the wrought (hot-rolled) condition this figure rises to about 7 tons per square inch, and even in the cold-drawn state, when its ductility has been almost entirely exhausted, the tensile strength does not exceed 10 tons per square inch. It is obvious, therefore, that pure aluminium cannot be employed where any considerable degree of strength or hardness is required. Incidentally, the softness and great ductility of the metal also render it difficult to machine, so that, for instance, it is difficult to cut satisfactory screw-threads in it. On the other hand, there are many uses in which the great ductility of the metal and its lightness are of value, while considerable strength is not required. In many spinnings and stampings, and in such articles as cooking-utensils, or even the much larger vessels employed in certain brewing and other chemical operations, the "pure" metal finds important applications. In many such cases it is employed on account of its indifference to certain chemical agencies. This is remarkable in view of the fact that aluminium is in reality a highly corrodible substance, which owes its continued existence in a moist atmosphere containing oxygen solely to the power which it possesses of becoming coated with a protective film—presumably of oxide. Provided that the agencies to which it is exposed in service do not remove or rupture this protective coating, the aluminium stands well. If, however, either by chemical or mechanical action the surface film is continually destroyed, rapid corrosion ensues. The behaviour of the alloys, to be discussed below, depends upon the same factors, with this modification, however, that the physical strength and the powers of chemical resistance of the protective film vary considerably according to the composition of the alloy—most alloys being distinctly less resistant than the "pure" metal. It is important to point out, in this connection, that commercially "pure"

aluminium may contain as much as 1 per cent each of iron and silicon, although prior to 1914 it was easy to obtain commercial aluminium containing not less than 99·3 per cent of the metal, while occasional samples attained 99·6 per cent. Recently, small samples of much purer aluminium have been prepared in the laboratory by special means, purity as high as 99·97 being obtained, and it is suggested that this high-purity metal has much greater powers of resisting corrosion. As yet, however, such claims have not been sufficiently established.

For a great many purposes, including the most important for which light metals are required, the strength of "pure" aluminium is entirely inadequate, and alloys are employed. In the choice of such alloys various considerations must be borne in mind. Perhaps the first of these is the question of density. Since these materials are valued for their specific lightness, it is evident that, of two materials of equal strength, that one having the lower density will be preferable unless other considerations, such as durability, etc., have to be taken into account. It is not a simple matter to define or determine the "strength" of any given type of material, since the power which a given alloy may possess to resist one particular system of stresses may not be—and frequently is not—proportional to its power of resisting some very different systems. Thus one alloy may have a very high tenacity, but its resistance to alternating stresses may be disproportionately low. As a rough general guide to the properties of a material, however, tensile strength, expressed in terms of ultimate or breaking stress, may be used, provided that the limitations of such a standard of comparison are borne in mind. From this point of view, the "figure of merit" of a material may be expressed in terms of the ratio of tensile strength to weight per unit volume. This ratio has been termed the "specific tenacity," [1] and may be expressed as a number which is the ratio of the ultimate tensile stress in tons per square inch to the weight of a cubic inch in pounds. It will be seen at once that the "Dimensions" of such a number are [Length], and, accordingly, there is a much simpler way of expressing the same facts. This method, which was used in a slightly different manner by Galileo, consists in stating the vertical length, in miles or feet, which a bar or rod of the material can just support. This length represents the weight of the material per unit area of cross-section which, when vertically suspended, exerts a total downward pull equal to the breaking stress of the material per unit area. The "specific tenacity" can thus be expressed simply in miles. Thus a mild steel having an ultimate strength of 30 tons per square inch can support a vertical length of its own material of 3·7 miles. The best of the wrought aluminium alloys now known has an equivalent length or specific tenacity of 14 miles. Pure aluminium gives only 2 miles.[2]

The alloying metals most usually employed with aluminium are copper and zinc, or, for some purposes, a combination of both. For purposes of castings, additions of copper up to 14 per cent have been used, and zinc has been added up to 25 or even 30 per cent. Where the materials are to be subjected to working, either hot or cold, and are to be used in the form of rod, sheet, or forgings or stampings, smaller proportions of alloying metals must be used. Since the requirements for castings and for wrought material are necessarily so different, it will be desirable to confine our attention in the first place to castings. Even among casting alloys, however, different considerations arise according to the uses for which the castings are intended; alloys which are quite satisfactory for use at the ordinary temperature becoming, in some cases, useless where higher temperatures have to be borne.

§ (2) Casting Alloys. (i.) *Copper-zinc Aluminium.*—For general casting purposes the most widely used type of alloy is one containing both zinc and copper, the proportions being generally of the order zinc 12 to 14 per cent, copper 2·5 to 3·5 per cent. In the chill-cast state such an alloy has a tensile strength of about 13 tons per square inch, with a specific gravity of 2·90. This corresponds with a specific tenacity of 4 miles. By increasing the zinc content, it is possible to obtain a higher specific tenacity, but this is combined with several disadvantages. Higher zinc content appears to increase the difficulty of obtaining sound castings, principally because the alloys become very weak and "tender" while hot and are apt to crack while cooling, either as the result of contraction stresses or as the consequence of slightly careless handling. Further, the higher specific tenacity does not, in castings, entirely counterbalance the effects of higher density. The reason lies in the fact that it is not possible to make the walls of castings thin enough fully to utilise the greater strength of the heavier metal, since for foundry reasons, and also in order to make the casting reasonably robust as against local damage, a certain minimum thickness is necessary. The composition named above is regarded, for the copper-zinc-aluminium series, as the best compromise, and the alloy has found very wide practical application. Large and complicated castings can be readily made of it, and it can be very easily machined. Other alloys,

[1] Tenth Report to the Alloys Research Committee, *Journ. Inst. Mech. Eng.*, 1912.

[2] Eleventh Report to the Alloys Research Committee, *Journ. Inst. Mech. Eng.*, 1921.

mentioned below, are, however, very likely to supersede this type in the near future, since they can be made to attain much greater strength, a much higher specific tenacity, and much greater resistance to corrosion—the latter being the weakest point in all aluminium alloys containing notable proportions of zinc.

(ii.) *Copper Aluminium.*—The alloys of aluminium with copper alone (4 per cent, 7 to 8 per cent, and 12 per cent have been widely used) present no advantage over the copper-zinc type when intended for use at ordinary temperatures. All aluminium alloys containing much zinc, however, show a very rapid falling off in strength with rising temperature. The alloys free from zinc and containing copper alone, or, better still, copper plus a small percentage of manganese, show a much lower rate of decline—one alloy containing copper 14 per cent and manganese 1 per cent is actually stronger at 250° C. than at the ordinary temperature. This matter of strength at moderately elevated temperatures is of the greatest importance in the use of aluminium alloys for such purposes as the pistons of internal combustion engines. Such a use appears at first sight remarkable in view of the fact that these alloys melt at temperatures in the neighbourhood of 600° C., while cast-iron pistons in aeroplane engines have been known to attain temperatures near 500° C. It is, however, the principal merit of the aluminium alloy piston to reduce very materially the temperatures attained by the walls and pistons of an internal combustion engine. This is due to the very high thermal conductivity of aluminium and its alloys as compared with steel (from 3·5 to 4·5 times). This lowering of the temperature, particularly during the compression stroke of the engine, not only brings about a very marked improvement in the efficiency and power output of the engine, but also reduces the maximum temperature to which the piston itself is exposed. In high-duty aeroplane engines it has been shown that the head of an aluminium alloy piston does not attain temperatures greatly exceeding 250° C. The more suitable alloys can easily withstand this temperature, and they have found very extensive use not only in aeroplane and airship engines, but also in some of the much larger Diesel engines used in submarines.

§ (3) Strength and Temperature.—The relative behaviours of a series of different alloys in regard to the effect of temperature on tensile strength is illustrated by the graphs shown in *Fig.* 1. The graph marked "L5" represents the behaviour of an alloy of the zinc-copper type such as that referred to above; it shows an immediate and rapid fall of strength with rise of temperature. The graph marked "Cu 12" shows the behaviour of an alloy consisting of 12 per cent of copper, remainder aluminium (plus impurities). This material shows considerably lower tensile strength at room temperature, but this strength does not fall off quite so rapidly as in the alloy L5. None the less, at 250° C. its tensile strength is not more than 7 tons per square inch. A striking contrast to these two alloys is presented by the alloy containing copper 14 per cent, manganese 1 per cent, whose behaviour is indicated in the correspondingly marked graph (14/1). Here the tensile strength actually rises from about 9 tons per square inch at room temperature to about 10 tons per square inch at 250° C. This behaviour is so anomalous that it has been repeatedly checked by several independent investigators; not only has this fact itself been firmly established, but it has been shown by the further observation that the elastic limit of proportionality (E_p) also rises from room temperature to

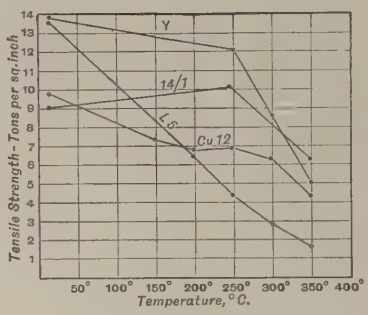


Fig. 1.

250° C. The underlying physical causes of this remarkable behaviour have not, however, been ascertained.

The fourth graph in *Fig.* 1, marked "Y," represents the behaviour of an alloy which has been comparatively recently developed by researches at the National Physical Laboratory. This alloy contains 4 per cent copper, 2 per cent nickel, and 1·5 per cent magnesium. In the chill-cast condition, this material has at room temperature slightly greater strength than "L5," combined with a lower density. Further, its strength falls off so slowly with rising temperature that at 250° C. it still shows 12 tons—a figure nearly double that of the previously widely used piston alloy containing 12 per cent of copper alone. It has further been found that by suitable heat treatment this alloy, even in the cast condition, can be made to attain a tensile strength as high as 19 or even 20 tons per square inch, and in this condition its strength at 250° C., even after prolonged exposure, is still over 12 tons per square inch. The heat treatment in question consists in first heating the casting, preferably in a salt-bath, at a temperature near 500° C. for

a period of about six hours, followed by quenching in boiling water.

§ (4) Advantages of Light Alloys.—Apart from the constantly increasing applications of the light alloys of aluminium for engineering purposes, there seems to be no doubt that, particularly in the cast condition, they offer remarkable advantages for the construction of many forms of scientific instrument. The greatest objection to them is often based on the idea that they are unduly liable to corrosion, but this fear is only justified in the case of instruments likely to be exposed to water or spray from the sea. Even there, however, efficient protection by means of a suitable varnish is perfectly possible, while polished surfaces which are frequently handled and are kept polished do not suffer at all readily. In other situations, however, these alloys prove to be extremely resistant to atmospheric corrosion; even the more corrodible alloys containing zinc do not tarnish or deteriorate as much as bare brass or bronze. As regards the combination of lightness with strength, there is of course no comparison between these alloys and brass, while the machining properties, particularly of the zinc alloys, is specially good. They are particularly suitable for all purposes where accurate machining and good finish are required. For a great many purposes in instrument construction, therefore, they are particularly well suited.

A question which is sometimes raised in regard to aluminium alloys intended for use in instruments is that of stability or permanence, apart from corrosion. Some instrument makers have undoubtedly met with unfortunate experiences in connection with die-castings which had been described as "aluminium." Careful investigation has, however, shown conclusively that the die-castings which caused trouble by spontaneous warping and, in some cases, by actual disintegration were not "light" alloys at all, but consisted of a large proportion of zinc with which *small* amounts of aluminium and copper had been alloyed. These zinc-rich alloys, when they contain both copper and aluminium, are now known not to be reliable or permanent.[1] On the other hand, extensive tests, over periods of more than seven years, have been made on castings consisting mainly of aluminium in the form of some of the alloys mentioned above, and it can be stated definitely that although the alloys undergo a series of slight internal changes which lead to a perceptible increase in their strength and hardness in the course of time, yet these changes are not accompanied by any changes of shape or volume which could be appreciated in their constructional use even in instrument work, unless the attempt were made to employ them for standards of length or work of the same grade of accuracy. For all ordinary purposes, therefore, the alloys may be employed with complete confidence in their permanence and stability. Only one point requires caution. In the cast condition, particularly if the casting is of complex form or is a hollow body, the high coefficient of thermal expansion of these alloys sometimes leads to the presence of internal contraction stresses. If the casting is used in that condition without further treatment, these stresses are unable to release themselves and no further effects result. If, on the other hand, the casting is machined in such a way as to cut away the outer skin either wholly or in part, slight changes of shape or dimension are apt to occur. Provided that the casting is allowed to adjust itself after a first roughing cut, these small changes have no evil effect, but if machining is very rapid and the article is completed before adjustment has taken place, subsequent slight distortion may occur. This is particularly liable to occur if the casting is afterwards exposed to an elevated temperature, and its occurrence accounts for the widely prevalent idea that aluminium alloy castings—and especially engine pistons—"grow" as the result of repeated heating and cooling. All such internal stresses can, however, be effectively removed by first heating the casting to a temperature of about 200° C. to 250° C., and then allowing it to cool slowly. Castings intended for use in high-class instruments should certainly be pre-annealed in this manner.

§ (5) Wrought Aluminium Alloys.—While aluminium alloys have undoubtedly found their widest applications in the form of castings, very great interest and importance also attaches to the wrought material, *i.e.* to the products obtained by such processes as rolling, forging, extrusion, stamping, spinning, etc. It is in the wrought condition that these materials have attained by far the highest combination of strength and lightness (*i.e.* specific tenacity), but at the same time very considerable difficulties have had to be overcome before the materials could be satisfactorily worked.[2]

§ (6) The Alloy "3/20."—The simplest of the "wrought" alloys is one which has been developed comparatively recently at the National Physical Laboratory, and is generally known as "Alloy A" or "3/20." The latter designation is derived from the fact that the alloy contains, besides aluminium, 3 per cent of copper and 20 per cent of zinc. In the form of hot-rolled bars or sheet this alloy attains a tensile strength of from 26 to 28

[1] "Zinc Alloys with Aluminium and Copper," Rosenhain, Haughton, and Bingham, *Journ. Inst. Metals*, 1920, vol. xxiii. No. 1.

[2] Eleventh Report to the Alloys Research Committee, *Inst. Mech. Eng.*, 1921.

tons per square inch, combined with a considerable degree of ductility as indicated by an elongation, on a gauge length of 2 inches, of from 18 to 25 per cent. By annealing at 250° C. this alloy can be rendered relatively soft and ductile, and can then be bent, stamped, or spun quite readily. In this condition it is safe and durable, provided it is given adequate protection from severely corroding conditions. On the other hand, the alloy possesses a remarkable peculiarity which must be borne in mind more in its manufacture than in its use. This is the circumstance that if it has been annealed for any length of time at temperatures *exceeding* 250° C. it is put into a condition—best described as "over-annealed"—in which it is liable to crack upon prolonged exposure to comparatively light stresses. This behaviour is in every way analogous to the well-known "season cracking" of brass. The explanation appears to be that, as a result of over-annealing, the alloy is found to consist of very regular crystals having smooth, almost rectilinear outlines, and these smooth crystal boundaries offer too little resistance to forces which tend to make them slide over one another or pull apart. This inter-crystalline motion is probably due to viscous or visco-elastic flow of the inter-crystalline cement (see "Metals, Relation of Strain and Structure"). Where the boundaries are rough and irregular, such flow cannot occur, and the material is free from the risk of "season cracking." This liability to damage through "over-annealing" constitutes a certain disadvantage to the alloy "A" (or "3/20"), but when properly treated the material is extremely useful. At the same time, this should be a relatively cheap alloy, because it contains a comparatively large proportion of the inexpensive metal zinc, and also because of the facility and simplicity of its production as compared with some other light alloys. Owing to the relatively high zinc-content, this alloy has a density of approximately 3·10, but none the less it attains a specific tenacity of 9 miles.

Of greater interest and importance, in some respects, than the alloy "A" ("3/20") itself are some of its derivatives. These have been arrived at, after extensive research, by the application to the alloy "A" of the hardening effect which, according to the important fundamental discovery of Wilm, can be produced by the addition of small amounts of magnesium to aluminium and its alloys. This hardening effect is more fully discussed below in connection with "Duralumin" and alloy "Y," but its application to the "3/20" type of material has led to very remarkable results. Thus one alloy, known as "E" (N.P.L.), can be made to attain a tensile strength of 39 tons per square inch, combined with an elongation of 16 per cent on a gauge length of 2 inches. This alloy, which contains, besides aluminium, approximately 18 per cent of zinc, 2·5 per cent of copper, 0·5 per cent of manganese, and 0·5 per cent of magnesium, has a density about the same as that of alloy "A" ("3/20"), *i.e.* 3·10, and has therefore a specific tenacity of 12·6 miles. In order to attain this condition, however, special heat treatment is required. This consists in heating the alloy to a temperature of 350° C., preferably in a salt-bath, followed by quenching in water. Immediately after quenching, the alloy is rather softer than before being heat-treated, but a hardening process rapidly sets in and the full hardness is attained in four or five days. The strength and hardness thus obtained appear to be entirely permanent, such gradual changes as occur in several subsequent years tending towards a slight further increase of hardness. There is no evidence at all that any of the hardened aluminium alloys undergo any softening or deterioration if kept at the ordinary temperature or below 100° C. The alloy "E," however, soon loses its great strength if heated beyond 150° C.

§ (7) Duralumin.—The best-known and most widely established of the wrought alloys of aluminium is undoubtedly that generally known as "Duralumin." This was the first alloy in which the property conferred by the addition of magnesium was utilised for practical purposes. The alloy is made in a range of compositions, but a typical analysis shows copper 4 per cent, manganese 1 per cent, magnesium 0·5 per cent. It has, however, recently been shown [1] that the real hardening agent in these alloys is not magnesium itself, but a compound of magnesium and silicon corresponding to the formula Mg_2Si. In the absence of silicon, or even of a sufficient amount of that element, the hardening effect disappears. The discovery of this fundamental fact, which appears to have been entirely overlooked by Wilm and his German colleagues, throws a strong light on the nature of the hardening phenomena in all aluminium alloys, and even on the hardening of steel. The behaviour of aluminium alloys of this general type (which includes Duralumin) is, at first sight, mysterious. After heating for a short time at a suitable high temperature, which in the case of Duralumin is between 480° C. and 500° C., followed by quenching or otherwise rapid cooling, the alloy is at first distinctly softer than it was before this treatment. Duralumin, for example, in the condition as rolled has a

[1] Eleventh Report to the Alloys Research Committee, 1921; and "Constitution and Age-hardening of the Alloys of Aluminium with Magnesium and Silicon," Hanson and Gayler, *Journ. Inst. Metals*, 1921, vol. xxvi. No. 2.

tensile strength of about 18 tons per square inch, with an elongation, on 2 inches, of about 16 per cent. Immediately after quenching the tensile strength is slightly lower (about 17 tons per square inch) and the elongation slightly higher. In the course of the first few hours after quenching, however, there is a marked rise in tensile strength, and this continues, at a decreasing rate, for about four days. At the end of that time the alloy has attained a tensile strength of from 25 to 27 tons per square inch, while the elongation has not receded appreciably below the value of the freshly rolled material—being sometimes slightly higher, *i.e.* about 18 to 20 per cent on 2 inches. Analogous phenomena are observed in other "hardening" aluminium alloys, such as the alloy "E" described above and the alloy "Y" (see below). It has further been shown that the rate of hardening after quenching, and even the maximum hardness attained, may be considerably increased by maintaining the alloy at a slightly elevated temperature during the ageing process. At all events, the state reached after a few days' ageing appears to be stable, although in the case of Duralumin a very gradual further ageing effect, tending to make the material rather harder and less ductile, appears to take place in the course of years—observations over a period of ten years are now available.

§ (8) Heat Treatment of Aluminium Alloys.—The whole process undergone by these alloys as the result of quenching and ageing bears a striking resemblance to the behaviour of certain alloy steels which are retained in the austenitic condition (see "Steels, Some Special") by quenching. In this condition they are soft and ductile, but in some cases they can be caused to become hard and magnetic by being slightly heated in a manner which would, in hardened carbon steels, bring about "tempering." In these steels, however, the result of tempering is a passage from the austenitic to the martensitic condition. Here the transformation is now recognised to arise from the separation of a substance or phase which had been retained in solid solution as a result of very rapid cooling; the separation of this previously dissolved phase *in a condition of extremely minute dispersion* gives rise to the great hardness of martensite. The close analogy of the aluminium alloys strengthens this explanation, since it has been shown that hardening of this kind only occurs where a compound is present which is more soluble in the solid matrix of the alloy at a high temperature than at lower temperatures. Quenching such an alloy retains the compound in solid solution in a meta-stable condition, leaving the alloy as a whole soft; if the quenched material is then kept at a temperature where the separation of the dissolved compound can occur gradually and in an extremely finely divided condition, gradual hardening by "tempering" will occur. In steels, such a tempering temperature is, generally, only attained by the aid of applied heat; in the aluminium alloys the temperature of the air is high enough to permit of the gradual occurrence of the process, which is accelerated by a slightly raised temperature, and can be entirely inhibited by keeping the metal at a very low temperature.[1]

Duralumin, in which this process had been practically utilised long before its true nature was understood, is thus a material which, by proper heat treatment, acquires remarkable properties as regards strength and ductility. Its behaviour offers the valuable possibility that the alloy can be wrought (cold-worked) while in a soft state and can then be hardened. On the other hand, once it has been hardened it must not be exposed to any temperature much above 150° C., otherwise its acquired hardness is lost. This renders it necessary to exercise great care and supervision wherever this alloy is employed, since it can be very seriously weakened by a slight amount of warming. The heat treatment itself also requires great care, since, at a temperature only a few degrees higher than that used for quenching, the alloy is liable to be irretrievably damaged. Used with proper care and skill, however, there can be no doubt of the great value of Duralumin, whose "specific tenacity" is represented by the figure 9 miles.

§ (9) The N.P.L. Alloy "Y."—An alloy which, while in composition and constitution entirely different from Duralumin, yet bears a certain resemblance to it, is that developed at the National Physical Laboratory under the name "Alloy Y." Initially developed as a casting alloy and valued largely for its relatively very high strength at elevated temperatures, it was found that this material, containing 4 per cent of copper, 2 per cent of nickel, and 1·5 per cent of magnesium, could be wrought by forging or rolling and was then capable of undergoing age-hardening after quenching. The presence of nickel in this alloy is of primary importance, since it is found entirely to alter the internal structure of the material. The compound $CuAl_2$, which forms so important a feature both in Duralumin and other aluminium alloys containing copper, is entirely absent, at all events in the heat-treated alloy "Y," being replaced by a body which appears to be a ternary compound of copper, nickel, and aluminium. The absence of $CuAl_2$ is important for several reasons, one of the most noteworthy being that the

[1] Merica. Waltenberg, and Scott, American Inst. Mining and Metallurgy, June 1919.

temperature at which incipient melting occurs is thereby considerably raised. This has the valuable effect that the heat-treatment (quenching) temperature to which this alloy can be safely subjected is considerably higher than in the case of Duralumin, while it is probably also responsible for the fact that the alloy "Y" shows distinctly greater resistance to fatigue stresses, particularly at slightly raised temperatures. The power of resisting corrosion also appears to be improved by the replacement of the copper-aluminium compound by the ternary body. For all purposes where resistance to moderately corrosive conditions is essential, and where strength at elevated temperatures is important, the alloy "Y" appears to offer very decided advantages. At ordinary temperatures its strength is approximately the same as that of Duralumin, so that from the point of view of specific tenacity alone it offers no advantage over Duralumin and is very much inferior to alloy "E," above. Alloy "Y," however, is the only one which has, so far as published data are concerned, been successfully used for the connecting rods of a high-speed internal-combustion engine. It has been used in one such engine to replace a set of mild-steel connecting rods of identical dimensions, and the substitution has appreciably improved the engine, not only on account of the reduction of weight of the reciprocating parts, but also as a result of the considerably greater cooling effect on the bearings derived from the high thermal conductivity of the alloy rods.

For the construction of scientific instruments, all the alloys which have been described above would appear to be available. Even alloys "A" and "E" do not suffer appreciably from atmospheric corrosion in an ordinary room or laboratory; Duralumin is more resistant, and alloy "Y" still more so. The latter material can well be used in either the cast or the wrought form. Alloys "A" and "E" are particularly satisfactory from the point of view of machining, "A" being superior in this respect to the best kinds of machinery brass. In many cases the saving of weight or the increased strength and stiffness obtainable by the use of these materials would prove of very considerable value.

W. R.

ALUMINIUM ALLOYS, heat treatment of. See "Aluminium Alloys," § (8).

ALUMINIUM-MAGNESIUM ALLOYS. See "Alloy Systems, Typical," § (7).

ALUMINIUM-MAGNESIUM-SILICON ALLOYS. See "Alloy Systems, Typical," § (24).

ALUMINIUM-ZINC ALLOYS. See "Alloy Systems, Typical," § (5).

Mechanical properties of. See *ibid.* § (5), Table IV.

AMORPHOUS PHASE, existence of, between crystals of metals. See "Iron-carbon Alloys," § (11).

AMORPHOUS PHASE THEORY: the theory that metals can, in certain circumstances, exist at the ordinary temperature in an amorphous, or vitreous condition, and that in this condition they are very much harder and stronger than in the crystalline state. See "Metals, The Relations of Strain and Structure," § (1).

Effect of solubility and hardening. See *ibid.* § (9).

Effects of strength and temperature. See *ibid.* § (5).

Effects of tempering and quenching. See *ibid.* § (8).

Experimental basis of. See *ibid.* § (3).

ANGLE-BARS, made from mild carbon steel: analysis; mechanical tests. See "Steels, Special," § (46), Table 9.

ANNEALING: heat treatment (generally heating for a certain period at some definite high temperature with slow cooling) for the removal of strain or hardness due to previous rapid cooling or cold working. See "Metals, Thermal and Mechanical Treatment of," § (11).

Of steel. See "Iron-carbon Alloys," § (10).

ANODE POTENTIAL IN COPPER CELL. See "Copper, Electrolytic Refining of," § (1).

ANODES FOR COPPER REFINING. See "Copper, Electrolytic Refining of," § (1).

ANTIMONY in steel. See "Steels, Special," § (29).

ARC FURNACE, direct: an arc furnace in which the arc is struck between an electrode and the charge. See also "Furnaces, Electric," § (2) (i.).

Indirect: an arc furnace in which the arc is struck between the electrodes and the charge heated by radiation. See also *ibid.* § (2) (ii.).

ARC FURNACES. See "Furnaces for Laboratory Use," § (5).

ARMAMENT STEELS. See "Steels, Special," § (53).

ARSEM VACUUM FURNACE. See "Furnaces for Laboratory Use," § (6).

ARSENIC in steel. See "Steels, Special," § (28).

Present in copper. See "Copper, Electrolytic Refining of," § (5).

AUSTENITE: a constituent of steel. See "Iron-carbon Alloys," § (5).

AUTOMOBILE STEELS: analysis; mechanical properties of. See "Steels, Special," § (46) (iv.), Tables 14, 15.

—B—

β-IRON. See "Iron-carbon Alloys," § (3).

BAUXITE, FUSION OF. See "Furnaces, Electric," § (5) (i.).

BEILBY: his theory of polishing based on the flow of solids under mechanical disturbance. His researches show conclusively that the production of a polish is due to the molecular flowing of the surface being polished. See "Solids, The Flow of."

BELAIEW, CRYSTALLISATION OF STEEL. See "Iron-carbon Alloys," § (7).

BENEDICKS, DILATATION OF IRON. See "Iron-carbon Alloys," § (3).

BINARY ALLOYS. See "Metals and Alloys, Micro-structure of," § (6).

Alloys containing only two elementary metals. See "Alloy Systems, Typical," § (1); "Steels, Special," § (11) (ii.).

BINARY SYSTEM, equilibrium diagram. See "Alloys, Constitution of."

BINARY AND TERNARY SYSTEMS OF REFRACTORY MATERIALS. See "Refractories," § (46).

BISMUTH in steel. See "Steels, Special," § (30).

BLOW-HOLES: small cavities found in ingots of cast metals, due to the imprisonment of bubbles of gas in the metal during solidification. See "Metals, Defects and Failure of," § (2).

BORON in steel. See "Steels, Special," § (17).

BRASS, FURNACES FOR. See "Furnaces, Electric," § (6).

BRASSES, SPECIAL. See "Alloys, Some Special," § (1).

BRINELL HARDNESS TEST, consists in the measurement of the impression made by a hardened steel ball under known load. See "Steels, Special," § (2).

BRONZES, SPECIAL. See "Alloys, Some Special," § (1).

—C—

CARBON: its presence in steel. See "Iron-carbon Alloys," § (6); see also "Steels, Special," § (21).

CARBON STEELS: analysis; strength. See "Steels, Special," § (1), Table I.

Influence of low temperatures upon physical properties of. See *ibid.* § (4) (A) (iii.).

CARBON TOOL STEELS as magnets. See "Steels, Special," § (9).

CARBON TUBE FURNACE. See "Furnaces for Laboratory Use," § (3) (*a*).

CARBONACEOUS REFRACTORIES. See "Refractories," § (42).

CARBORUNDUM, CHEMICAL AND PHYSICAL PROPERTIES. See "Refractories," § (54).

"CASCADE" FURNACE: a graphite resistance furnace, built on the cascade principle described by Northrupp. See "Furnaces for Laboratory Use," § (3).

CASE-HARDENING: production of an outer layer of hardened, highly carbonised steel on an article of soft steel. See "Iron-carbon Alloys," § (13); "Metals, Thermal and Mechanical Treatment of," § (12); "Steels, Special," § (45).

CAST IRON. See "Iron-carbon Alloys," § (15).

CAST STEEL, structure of. See "Iron-carbon Alloys," § (8).

Transformation to forged steel by mechanical treatment. See *ibid.* § (8).

CASTING, differences in structure and physical properties between outer and inner portions of. See "Metals, Thermal and Mechanical Treatment of," § (3).

Pouring molten metal into moulds, allowing it to cool, then opening the moulds and removing the finished casting. See *ibid.* § (2).

CASTING ALLOYS. See "Aluminium Alloys," § (2).

CATHODE RAY FURNACE. See "Furnaces for Laboratory Use," § (8).

CEMENTATION OF STEEL. See "Iron-carbon Alloys," § (13).

CEMENTITE. See "Iron-carbon Alloys," § (6).

Excess absorbed by austenite in cast steel. See *ibid.* § (8).

CEMENTITE FILMS IN STEEL: fracture caused by cold work. See "Iron-carbon Alloys," § (10).

CHROMIUM in steel. See "Steels, Special," § (31).

CHRONIC: a trade name for an alloy consisting essentially of nickel, chromium, and iron. See "Furnaces for Laboratory Use," § (1); see also "Alloys, Some Special," § (2).

Clay Refractories, analyses of. See "Refractories," § (21).
Expansion of. See *ibid.* § (26).
Porosity of. See *ibid.* § (27).
Softening-point of. See *ibid.* §§ (20), (22).
Specific gravity and other physical properties. See *ibid.* §§ (28)-(30).
Strength of. See *ibid.* §§ (23), (24).

Clays, Refractory. See "Refractories," § (5).
Deflocculation of. See *ibid.* § (7).
Effect of heat on. See *ibid.* § (8).
Plasticity of. See *ibid.* § (6).
Porosity of. See *ibid.* § (9).

Clocks, compensation of, use of invar for. See "Invar and Elinvar," § (11).

Cobalt in steel. See "Steels, Special," § (38).

Cobalt Alloys as magnets, coercive force 200-240. See "Steels, Special," § (9).

Cold Working: producing changes of shape in a metal by the application of stress while the metal is cold. See "Metals, Defects and Failure of," § (4).

Colloidal Substances, forms produced in, by surface tension; investigations of Lehmann and Quincke. See "Solids, The Aggregation of."

Contact Resistance Furnace. See "Furnaces for Laboratory Use," § (3) (*d*).

Cooling Curve in construction of equilibrium diagram. See "Alloys, Constitution of," § (2) (iii.).

Cooperite: a hard, non-ductile alloy, used in the manufacture of cutting-tools. See "Alloys, Some Special," § (3).

Copper, sources of British importation of. See "Copper, Electrolytic Refining of."
Effect of low temperatures on physical properties of. See "Steels, Special," § (4) (A) (ii.).
In steel. See *ibid.* § (13).

COPPER, THE ELECTROLYTIC REFINING OF

The electrolytic refining of copper takes place by means of the electrolysis of a solution of copper sulphate between an anode of the raw material and a cathode plate on which the purified copper is deposited, the object being the production of High Conductivity Copper for telegraphic and general electrical purposes, and the recovery of the rare metals from the crude copper.

The conditions governing this method of copper refining vary considerably, and it is difficult to give information to-day which will be of practical value to the refiner ten years hence. The reason for this is that the raw material arriving in this country over one decade is totally different from that of another decade.

From 1891 to 1901, the copper sent to this country was from the United States, and arrived in the form of matte containing about four hundred ounces of silver to the ton. There were few other impurities to contend with, and the electrolysis was comparatively simple, except that there was little previous electro-chemical experience to guide us.

From 1901 to 1911 most of the copper arrived in the form of ores and blister copper from America, Japan, Chili, Australia, and East Africa, and contained large quantities of bismuth and antimony, both extremely difficult metals to eliminate without contaminating the cathode copper during electrolysis.

From 1911 to 1921 scarcely any ores were imported, and the raw material arrived as bar copper, containing very little bismuth or antimony, but large quantities of arsenic.

The refiner must, therefore, be prepared to adjust his electrolytic plant periodically to meet altered conditions.

Taking a typical anode to-day, assaying

Copper	97·5 per cent,
Arsenic	1·334 „
Antimony	0·5 „
Nickel	0·4 „
Lead	0·243 „
Iron	trace,
Silver	10 oz. per ton,
Gold	3 dwts. „

the arsenic content does not appear to be very excessive, but in a plant having an output of one hundred tons per week capacity, there would be 8170 grains of arsenic per gallon in the electrolyte at the end of twelve months' working, provided all the arsenic went into solution, whereas an arsenic content of 3000 grains per gallon is found in practice to be the limit for the production of pure copper. Fortunately, a large proportion of the arsenic remains in the arsenic state with the insoluble residues, but a considerable quantity goes into solution as arsenious acid.

The usual arsenic content of the electrolyte is 1500 grains per gallon after six months' working. When the arsenic content of the electrolyte exceeds 3000 grains to the gallon, the conductivity of the electrolytic copper deposited may fall as low as 91 per cent, and great additional expense is entailed in the subsequent treatment of the copper in the wire-bar furnaces. The same trouble occurs when the bismuth content exceeds 300 grains per gallon.

A portion of the electrolyte should, therefore, be removed daily, and fresh solution added.

§ (1) Preparation of Anodes.—The chief point to decide is, how much refining of the

copper shall be carried out in the anode furnace, and how much shall be left to electrolysis.

The anode should certainly have a minimum copper content of 97 per cent, for the purer the anode the greater the gain both practically and financially to the manufacturer. Anodes assaying as low as 97 per cent copper will be found difficult to cast satisfactorily. They will disintegrate unevenly in the depositing vats, the scrap will run up to 30 per cent, and the electrolyte will become foul in a very short time. Then, again, the resistance of the circuit is greatly increased by the presence of excessive quantities of nickel, antimony, and arsenic in the anodes. The smelter, therefore, should deliver anodes of 98 per cent copper to the electrolytic plant if possible. If impurities such as nickel and antimony are left in the anode, they will form an insoluble coating on the surface of the anode, and behave as a partially insoluble anode, robbing the electrolyte of its copper content, and offering a high resistance to the electric current. Then, again, some precipitates are very much more bulky than others, and unless ample clearance has been allowed for between the electrodes and the bottom of the vats, short-circuiting will ensue before the electrodes are worked out.

With a fairly pure anode the E.M.F. of a cell will be only 0·2 volt; whereas with an impure anode, as much as four times the voltage may be required. This may be partially counteracted by increased temperature of the electrolyte and the addition of sulphuric acid, but not entirely.

If the electrolyte could conveniently be maintained at 130 degrees F., it would be found that the slimes leave the surface of the anode and fall to the bottom of the vat, thereby materially reducing the resistance of the cells. In practice, however, a temperature of 105° is rarely exceeded, and this causes no discomfort to those engaged in working the process.

The dimensions of the plates vary considerably according to the system used in the refinery.

§ (2) Depositing Vats.—The vats may be arranged either in series or parallel.

If the series system is used, slate vats 2 inches thick, 6 feet 6 inches long, 3 feet wide, and 2 feet deep, are lined with a composition consisting of pitch, resin, and plaster of Paris, in the following proportions, viz.: pitch 7 parts (by volume), resin 4 parts, plaster of Paris 2. The pitch is first melted, the resin then added, and finally the plaster of Paris sprinkled on the surface, and the whole stirred for an hour. When the foam has subsided, the composition is laded into buckets, and the bottom of the vat is lined 1½ inches thick. The negative connection, consisting of tape copper 2 inches wide by ⅛th inch thick, is then placed in position, and wooden frames whitewashed on the inner side are placed around the sides and ends 2 inches from the slate, and all joints filled with a putty consisting of china-clay and tar. The sides and ends are then slowly cast so as not to crack the slate by sudden heating. After twenty-four hours, the casting has set hard, and the wooden frames are removed. If the limewash is thoroughly dry before casting, it will leave the lining without adhering. The lining is now ironed, and is good for several years at any temperature up to 110 degrees F. with occasional ironing and patching with the composition when leakages occur at the joints. The tie-bolts of the vat should be left slack during casting to allow for expansion, and screwed up when the casting begins to cool. It is usual to fill the slate grooves with red lead and oil when erecting the vats.

The negative conductor (see *Fig.* 1), supported at the foot by a glass block C, is now

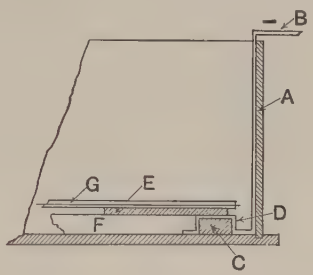


Fig. 1.

cleaned, and the cathode plates laid on wooden spars along the bottom of the vat. Above this the calico filter is stretched to receive the insoluble residues, and then alternate rows of plates and filters for ten rows. The top row of plates is thicker than the intermediate rows, and on this row the positive connection plate rests as shown in *Fig.* 2. The plates are

Fig. 2.

2 feet 10 inches long, 9 inches wide, and ⅜th inch thick, and weigh 38 pounds each, so that the vat, when fully packed, contains about 30 cwts. of copper.

If the multiple or parallel system is used,

lead-lined wooden vats are employed of any convenient dimensions, usually about 5 feet long, 2 feet 3 inches wide, and 3 feet 6 inches deep, and anodes 3 feet by 2 feet hanging from the positive conductors.

On the series system, the plant is usually split up into units, each unit taking 250 amperes at 100 to 120 volts. The reverse side of each anode acts as a cathode, and must be coated with some "stripping" material to enable the cathode copper to be removed from the undissolved anode. The nature of this insulation materially affects the nature of the cathode copper, as will be pointed out later on.

On the parallel or multiple system, the current usually ranges from 1500 to 2000 amperes and 50 volts. The electrodes are crude anodes and pure sheet copper cathodes suspended alternately along the conductors, with a space of 2 inches between each plate (see *Fig.* 3). In this case no coating material

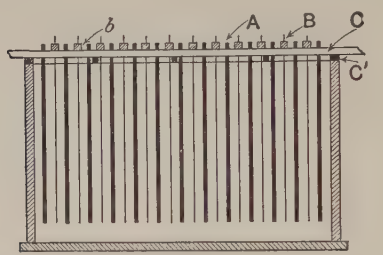


FIG. 3.

is necessary, as the cathode sheets become embedded in the cathode.

Both systems have their advantages and disadvantages, but after fifteen years' working on each, the writer recommends the parallel or multiple system.

The disadvantages of the series system are high E.M.F. of the circuit with the attendant liability to current leakage through the circulating pipes and earth, the inconvenience of pitch-lined slate tanks, and the tedious process of stripping the scrap from the cathodes; on the other hand, the low cost of repairs to the generators and the small section of the copper conductors are favourable factors. The disadvantages of the parallel system are the manufacture of cathode sheets, the large cross-section of the conductors, and the heavy repairs to the brush-gear of the generators, but on this system lead-lined vats may be used, and better insulation of the vats is thereby ensured.

The output per B.T.U. is the same in both cases.

§ (3) ELECTROLYTE.—The electrolyte should contain 3 per cent of copper and 15 per cent of free sulphuric acid. The usual method of making up the solution on a commercial scale is to dissolve blue-stone crystals in water until a uniform density of 10 Beaumé is obtained, then adding sulphuric acid until the solution has attained a density of 20 Beaumé (cold). This method saves time in calculating the volume of sulphuric acid of different strength required to give a 15 per cent content, and since the acid received from vitriol makers varies considerably from day to day, is one to bear in mind.

The electrolyte is then heated by means of lead steam-coils (usually exhaust steam from engines being used), and freely circulated for twelve hours before switching on the current. The density of the electrolyte should never exceed 20 Beaumé (31 Twaddell) at 110 degrees F., otherwise the insoluble slimes will float about in the vats and become embedded in the cathode copper.

When nickel is present in the anode, there is a great tendency for the electrolyte to become sticky owing to the presence of nickel sulphate as well as copper sulphate in solution.

The electrolyte should be tested for copper every morning by the cyanide method, and for acid by a standard soda solution (titration).

Owing to the impurities present in the anodes, the copper content will be found to fall each day, and a small quantity of blue-stone must be added to keep up the required strength.

Sulphuric acid must also be added periodically. Taken over a period of twenty-five years, the quantity of acid works out at one ton for every twenty tons of copper deposited.

The rate of circulation of the electrolyte must not be less than one gallon per minute, and the electrolyte in each vat should be completely changed once every five hours. Pumping the electrolyte to the supply cisterns, which twenty years ago gave so much trouble, is now a simple matter since the advent of acid-resisting centrifugal pumps, and by means of clockwork devices or worm-gearing the volume of liquid passing through the circuit may be regulated to a nicety.

§ (4) WORKING THE VATS.—A newly packed vat will offer a high resistance to the current for twenty-four hours owing to the low temperature of the electrodes, but when these have reached the temperature of the electrolyte, the resistance will be found normal. On starting off a completely new circuit, it is advisable to keep the current density down to ten amperes per square foot and gradually increase this to 15-20 amps. Flashing the cathodes with a high current as is done in electroplating must never be practised in the electrolytic refining of crude anodes, otherwise the first coating of copper will be loose and may float about in the electrolyte, and cause a rough nodular deposit for the remainder of

the period during which the vats are in operation.

If the anodes are ¾ inch in thickness, the vats will be ready to be emptied after twenty-one days' working, when the cathodes are removed by the overhead travelling crane and washed in situ, and the rich slimes flushed through the outlet pipe on to a specially constructed filter, for subsequent drying and copper extraction.

Each individual vat should be tested with a delicate voltmeter twice daily in order to detect any short-circuiting between the electrodes, and an ammeter should be fixed at the end of each row of vats to ensure the current being equally distributed through the circuit.

Residues.—The insoluble residues from the anodes contain roughly,

Copper	15 per cent.
Arsenic	8 „
Antimony . . .	16 „
Nickel	4 „
Lead	2 „

in addition to the silver and gold, which vary considerably.

The treatment of these residues is too large a subject to include under this heading, and is really a purely chemical operation usually carried out by silver or bullion refiners.

It is usual to pass the residues through a Dehne filter press fitted with wooden frames and brass screens, and calcine the cakes at a low temperature so as to oxidise the metallic copper and cuprous oxide to the cupric state, and dissolve out the copper in agitators fitted with metallic copper sheets to prevent the silver going into solution. The residues are then dried and marketed.

§ (5) Weight of Electrolytic Copper per B.T.U.—The weight of electrolytic copper deposited per Board of Trade unit varies with the degree of impurity in the anode, the internal resistance of the vats, and the drop of the voltage between the generators and the vats. Under bad management the output may be as low as 4·5 pounds of electrolytic copper per unit, and under good management may be as high as 9 pounds per B.T.U.

Taking the figure on a thirty years' run, during which accurate figures have been kept and over one hundred thousand tons of copper deposited, the output during the first twenty years worked out at thirteen tons of electrolytic copper per E.H.P. year, against fifteen tons per E.H.P. year during the last ten years.

The increased efficiency of the latter period is partly due to greater skill on the part of the workmen engaged in testing the vats, and partly due to purer anodes being used. Twenty years ago it was a daily occurrence to find at least one pitch-lined wooden vat on fire through short-circuiting, whereas such a thing is unheard of to-day, because vats are now raised well above the floor level, leakages can at once be detected, porcelain insulators are easily procurable at a low figure, and better circulating systems for the electrolyte have been adopted.

§ (6) Power Supply.—Whether power is obtained from a public supply or generated on the spot is simply a matter of convenience. By tapping a public supply, the inconvenient stoppages for boiler-cleaning and general repairs are obviated, and floor space is saved where ground rents are high, but the cost of power is practically the same in both cases, taking depreciation and repairs into consideration.

§ (7) Capital required.—Owing to the large amount of money locked up in an electrolytic plant of any size, it is important that the highest possible current density per square foot should be maintained, and this can only be done with good anodes.

The men who cast the anodes should be paid according to the weight of scrap, otherwise there is no incentive to lade the plates uniformly, and a reduction of as much as 10 per cent in the weight of scrap can be effected in this manner.

Taking a plant with an output of 100 tons per week, or 5000 tons per year, we have 600 tons of dead stock at say £100 per ton, equal to interest at the rate of 12s. per ton of copper deposited. The interest in this case is equivalent to the cost of the whole of the power used in depositing the copper. With a little extra care, the same 600 tons of dead stock may be made to produce 6000 tons of copper instead of 5000 tons, and if the value of the precious metals, electrolyte, and standing charges are included, the interest will be still greater, and there is no reason why a current density of 25 amperes per square foot should not be maintained regularly.

§ (8) Anodes. — Large anodes may save labour in packing the vats, but they are most wasteful in practice, and they should never exceed 3 feet by 2 feet, otherwise they cannot be cast evenly, and they will not disintegrate uniformly in the vats. The writer prefers plates half this size for economical working.

On the multiple system, the size and smoothness of the anodes is not nearly so important as on the series system, because the anodes are attacked by the current from both sides, and any protuberances present on the surface are eaten away before, or more quickly than, the remainder of the plate owing to their being nearer to the cathode sheet; but where the electrodes are arranged in series in the vats, and each electrode acts as an anode

cathode, the back of the anode should be smooth and coated with some "stripping" material for subsequently separating the cathode from the remains of the undissolved anode. The path of the current, also, is not directly from anode to cathode, and there is always greater action on the edges of the plates than in the centre, with the result that a portion of the copper which has been deposited on the edges of the cathode is redissolved and redeposited with wasteful results. And again, if there are pit-holes in the back of the anode, these will be reproduced in the cathode, and trouble with the stripping will result.

§ (9) Addition Agents and Stripping Materials.—Much has been written on the subject of "Addition Agents to the Electrolyte," more especially for electroplating, where the metal deposited is required to be very smooth and tough. This is of little importance when the deposited metal is to be melted down for wire-bars, but at the same time a good homogeneous tough cathode is better for handling than a brittle one, distinctly better for shearing where cut cathodes are wanted for brass-founders, and as a rule a tough cathode is found to be purer than a brittle one. This does not necessarily follow, as may be proved by coating a copper sheet with animal blood. If copper be deposited on this half an inch in thickness, it will be so brittle that it may be broken between the fingers, although it is perfectly pure.

For about ten years the writer used hot paraffin wax as a stripping medium for the series system, and obtained good strong cathodes all the time. Over another period when the price of wax made its use prohibitive, stearine melted and dissolved in benzine was used, and the same strong cathodes were obtained. Subsequently a mixture of carbon and paraffin was adopted, which reduced the cost of stripping 50 per cent, but made the cathodes very brittle indeed though still pure.

This, however, was not entirely due to the receiving surface. A high current density was being employed in all three instances, similar anodes were being refined, and subsequent experiments disclosed the fact that, with paraffin wax or stearine on the plates, a portion of these was mechanically suspended in the electrolyte with beneficial results, and, by adding stearine to the electrolyte, carbon might still be used as the stripping medium, and strong cathode copper be deposited.

The same beneficial results may be obtained by using gelatine in small quantities, but a 2-cwt. drum of stearine placed in the supply cistern will slowly dissolve and give the requisite amount of grease to produce tough cathodes. Graphite, on the other hand, tends to produce a spiky deposit similar to the drum of a musical box.

Any violent disturbance of the electrolyte causes the tree-like formation so often found on a large plant.

§ (10) Automatic Syphons. — In order to prevent short-circuiting from vat to vat through the circulation pipes, it is advisable to fix an automatic syphon box on each vat, which will quickly empty itself when the liquor rises to a certain height, and so break the connection.

§ (11) Filtering.—If the electrolyte cannot be conveniently filtered in its passage to and from the vats, large settling vats should be provided to catch particles of organic matter and other insoluble substances which might otherwise become mechanically embedded in the cathodes.

In describing the series system above, the use of calico filters between each row of electrodes is only necessary where the plates are packed horizontally in the vats, as in "Smith's process." When the plates are suspended vertically, and each plate acts as an anode/cathode, no filters are needed, but the horizontal arrangement gives a smoother deposit, and the tendency towards short-circuiting is greatly reduced. The acidity of the electrolyte may also be varied between 3 per cent and 15 per cent, and the copper content from 1½ per cent to 6 per cent.

Considering the fact that electrolytic refining of copper has been practised in this country for over thirty years, it is surprising that so few improvements have been made in the casting of the anodes, reduction in the weight of scrap, and output per Board of Trade unit.

H. E. D.

Copper Alloys. See "Metals, Thermal and Mechanical Treatment of," § (1).

Copper-aluminium: a light alloy. See "Alloy Systems, Typical," § (4); "Aluminium Alloys," § (2) (ii.); also "Alloys, Some Special," § (1) (iv.).

Copper-aluminium Alloys, mechanical properties of. See "Alloy Systems, Typical," § (4), Table III.

Copper-aluminium-magnesium Alloys. See "Alloy Systems, Typical," § (22).

Copper-aluminium-manganese Alloys. See "Alloy Systems, Typical," § (23).

Copper-aluminium-tin Alloys. See "Alloy Systems, Typical," § (20).

Copper-aluminium-zinc Alloys. See "Alloy Systems, Typical," § (21).

COPPER-MANGANESE ALLOYS. See "Alloy Systems, Typical," § (10).

COPPER-NICKEL ALLOYS. See "Alloy Systems, Typical," § (6); "Alloys, Some Special," § (1) (v.).
Mechanical properties of. See "Alloy Systems, Typical," § (6).

COPPER-NICKEL-ZINC ALLOYS. See "Alloy Systems, Typical," § (18).

COPPER-PHOSPHORUS ALLOYS. See "Alloy Systems, Typical," § (13).

COPPER REFINING, ADDITION AGENTS IN. See "Copper, Electrolytic Refining of," § (9).

COPPER-TIN ALLOYS. See "Alloy Systems, Typical," § (3).
Mechanical properties of. See *ibid.* § (3), Table II.

COPPER-ZINC ALLOYS. See "Alloy Systems, Typical," § (2).
Mechanical properties of. See *ibid.* § (2), Table I.

COPPER-ZINC-ALUMINIUM: a light alloy. See "Aluminium Alloys," § (2) (i.).

COPPER-ZINC-TIN ALLOYS. See "Alloy Systems, Typical," § (19).

CRACKS in steel as a result of internal stress. See "Iron-carbon Alloys," § (11).

"CRITICAL" ILLUMINATION, obtained when a sharply focussed achromatic or apochromatic image of a uniform source of light is thrown upon a surface under microscopic examination. See "Focussed Lighting"; "Metals, Microscopic Examination of," § (6).

CRUCIBLES FOR LABORATORY WORK. See "Refractories," § (45).

CRYSTAL BUILDING IN METALS. See "Metals and Alloys, Micro-structure of," § (6); see also "Crystallography," § (15), Vol. IV.

CRYSTALLINE CHARACTER OF METALS. See "Metals and Alloys, Micro-structure of," § (2).

CRYSTALLINE CONDITION of two metals solidifying from a mutual liquid solution. See "Metals and Alloys, Micro-structure of," § (6).

CRYSTALLINE GRAINS. See "Metals and Alloys, Micro-structure of," § (5).

CRYSTALLINE METAL. See "Metals, The Relations of Strain and Structure," § (2).

CRYSTALLINE NATURE OF METALS. See "Metals and Alloys, Micro-structure of," § (2).

CRYSTALLINE STRUCTURE, changes of, in a metal. See "Metals and Alloys, Micro-structure of," § (5).
Of nearly pure iron. See *ibid.* § (3).

CRYSTALLISATION OF STEEL, according to Belaiew. See "Iron-carbon Alloys," § (8).

CRYSTALS in two metals "soluble in the solid." See "Metals and Alloys, Micro-structure of, § (6).
Outward growth of, from a nucleus in a cooling mass of metal. See *ibid.* § (4).

CRYSTALS, SOLUBILITY OF SMALL, comparatively greater than that of large. See "Solids, The Flow of."

CURRENT DENSITY in copper electrolysis. See "Copper, Electrolytic Refining of," §§ (4) and (7).

CURVE TRACER, Brearley. See "Metals, Thermal Study of," § (6).

CUTLERY STEELS: carbon steels suitably hardened and tempered to give the required hardness, the "stainless" property being obtained by the addition of about 14·0 per cent chromium; analysis. See "Steels, Special," § (47) (iii.), Table 17.

CUTTING-TOOLS, alloys used in the manufacture of. See "Alloys, Some Special," § (3).

CYANAMIDE, PRODUCTION OF. See "Furnaces, Electric," § (10).

— D —

DEGREES OF FREEDOM in a system of alloys. See "Alloys, Constitution of," § (1) (iii.).

DENT'S ERROR: an error of a chronometer, discovered by Dent, compensated by use of a special alloy. See "Invar and Elinvar," § (12).

DEVILLE FURNACE. See "Furnaces for Laboratory Use," § (12).

DIFFERENTIAL METHOD OF ROBERTS-AUSTEN FOR OBTAINING THERMAL CURVES. See "Metals, Thermal Study of," § (7).

DILATATION OF IRON. See "Iron-carbon Alloys," § (3).

DILATATION OF STEELS. See "Steels, Special," § (6).

DIRECT ARC FURNACE: an arc furnace in which the arc is struck between an electrode and the charge. See "Furnaces, Electric," § (2) (i.).

DIVARIANT SYSTEM OF ALLOYS, example of. See "Alloys, Constitution of," § (1) (iv.).

Drop-forging: pressing metal into the desired final shape from rolled bars or sheets, usually while hot. See "Metals, Thermal and Mechanical Treatment of," § (9).

Duralumin: an alloy of aluminium, containing in a typical analysis 4 per cent of copper, 1 per cent of manganese, and 0·5 per cent of magnesium. See "Aluminium Alloys," § (7).

— E —

Electrical Conductivity, as a means of interpreting changes taking place in steel with varying composition and heat treatment. See "Steels, Special," § (11).

In relation to compositions of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (2).

Electrodes, composition and manufacture of. See "Furnaces, Electric," § (3) (ii.).

Electrolytic Potential in relation to compositions of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (7).

Electromotive-force, measurement of thermal. See "Metals, Thermal Study of," § (4).

Electron Theory in relation to thermal conductivity of steels. See "Steels, Special," § (10).

Electroplating: applying a coating of metal to an object by means of electrolysis. See "Metals, Defects and Failure of," § (6).

Elinvar. See "Invar and Elinvar," §§ (1) and (13).

Equilibrium Diagram of binary alloys. See "Metals and Alloys, Micro-structure of," § (7).

For a series of alloys. See "Alloys, Constitution of."

Limitations of. See *ibid.* § (8).

Microscopic examination for constructing. See *ibid.* § (2) (ii.).

Of iron-carbon system. See "Iron-carbon Alloys," § (7).

Thermal method for constructing. See "Alloys, Constitution of," § (2) (i.).

Uses of. See *ibid.* § (8).

Etching: subjecting the polished surface of a metal or alloy to the action of a suitable reagent in order to develop its constitutional and crystalline structure. See "Metals, Microscopic Examination of," § (2).

Eutectic of a binary system. See "Metals and Alloys, Micro-structure of," § (7).

Eutectic Alloys. See "Metals and Alloys, Micro-structure of," § (7).

Eutectiferous Alloy, behaviour during cooling and solidification. See "Metals and Alloys, Micro-structure of," § (7).

Expansion of Steels. See "Steels, Special," § (6).

Extrusion: forcing metal which is usually heated, under high pressure, through an aperture of the shape to be produced. See "Metals, Thermal and Mechanical Treatment of," § (8).

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Ferrite. See "Iron-carbon Alloys," § (2).

Excess absorbed by austenite in cast steel. See *ibid.* § (8).

Ferrosilicon, furnace for manufacture of. See "Furnaces, Electric," § (4) (iii.).

Fire Cracking may occur when a bar or slab of metal is put into the annealing furnace after too light a reduction process. See "Metals, Thermal and Mechanical Treatment of," § (6).

Fireclay Articles, drying of. See "Refractories," § (17).

Casting of. See *ibid.* § (11) (iii.).

Firing of. See *ibid.* § (18).

Manufacture of. See *ibid.* § (11).

Moulding. See *ibid.* § (17) (i.).

Pressing. See *ibid.* § (11) (ii.).

Flame Temperature of a Bunsen Burner. See "Furnaces for Laboratory Use," § (9).

Foam-cells, formed by the eutectic in the solidification of a mixture of two metals, Quincke's hypothesis of. See "Solids, The Aggregation of."

Focussed Lighting, obtained when a sharply focussed achromatic or apochromatic image of a uniform source of light is thrown upon a surface under microscopic examination. See "Critical Illumination"; "Metals, Microscopic Examination of," § (6).

Forged Steel, mechanical treatment of. See "Iron-carbon Alloys," § (9).

Forging: shaping and working metal by hammering, at elevated temperatures. See

"Metals, Thermal and Mechanical Treatment of," § (5).

FORGINGS, LARGE. Analysis; mechanical properties. See "Steels, Special," § (46) (iii.), Tables 11, 12, 13.

FRACTURE PATH in metals. See "Metals, The Relations of Strain and Structure," § (4).

FURNACES, ELECTRIC

§ (1) GENERAL PROPERTIES.—The extremely high temperatures which can be readily obtained by electrical means naturally suggest that source of heat energy for various processes which require the attainment of temperatures approaching or even exceeding the maximum attainable by the combustion of fuel. The earlier uses of electric furnaces were therefore naturally confined to processes of this kind; but with the development of the electric furnace it has been found that, for various reasons, electricity is a more economical and convenient source of heat than the combustion of fuel in processes where temperatures by no means excessively high are required. An example of this use of electric heating in metallurgical work at relatively low temperature is found in apparatus which are sometimes classed as electric furnaces, but which will not be included in this article, viz. those used in the electrolysis of fused electrolytes. In such cases it is obviously more economical and convenient to use a portion of the electric energy in the form of heat for fusing the electrolyte, the remainder effecting the electrolytic reaction.

In the electric furnace proper there is nothing in the work performed in it which demands the use of electricity as such. The work is simply a kind which requires heat, and the source of that heat is electrical, either because the temperature required is so high that it is not possible to attain it economically by other sources of heat, or because, even though the actual cost of the heat units produced electrically is greater than that of heat units supplied by combustion, the saving in other costs, such, for example, as labour, is so great as to counterbalance the higher cost of electrical heat.

The unit of electric power or rate of generation of energy is the watt, but since even relatively small electric furnaces have considerable capacity, the unit of power generally employed is the kilowatt (1000 watts) and the unit of energy the kilowatt hour. In measuring the heat units supplied to an electric furnace, the large calorie, *i.e.* the quantity of heat required to raise 1 kilogram of water 1° Centigrade, is used. One British Thermal Unit (B.T.U.) is equivalent to 0·252 calorie (large). The quantity of heat available in any electric furnace can be calculated from the following equation:

1 kilowatt hour = 860 calories.

To generate this amount of heat by means of combustion of fuel would require about 120 grams (4·2 ounces) of a good bituminous coal or 80 grams (2·8 ounces) of fuel oil. This would at first sight make it appear that the electrical generation of heat is enormously expensive and that it could hardly compete with the methods depending on the combustion of fuel. Thus if coal cost sixty shillings per ton the cost of 860 calories generated by its combustion would be 0·085 penny, and it is only under somewhat exceptional circumstances that 1 kilowatt hour can be obtained at that price.

There are, however, other considerations to be kept in mind which show that, in spite of the high cost of the heat unit generated electrically, it is cheaper to heat in that way because the electrically generated heat can accomplish the work in view with a far smaller number of heat units than fuel, and because in some cases the work can only be done practically by electric heat.

For example, it has been estimated that in certain work requiring the application of heat the thermal efficiency in a fuel-fired furnace is so low that only 5 per cent of the heat generated is used in doing the work required, while the remainder is expended wastefully. If, in an electric furnace doing the same work, 80 per cent of the heat generated is usefully employed and only 20 per cent wasted, then taking the figures used for illustration above, the amount of coal required to generate 860 calories of useful heat would be 2·4 kilograms (5·3 pounds) and would cost 1·7 pence, while the electrical energy required would be only 1·25 kilowatt hours.

The relatively high efficiency of electric furnaces as compared with fuel-fired furnaces may be explained as follows:

In a fuel-fired furnace, for example one burning carbon in some form, the carbon combines with oxygen and in so doing generates a quantity of heat which raises the resulting carbon monoxide gas to a high temperature. The heat in this gas is then transferred by conduction or radiation to the furnace charge. When the difference between the hot gases of combustion and the furnace charge is very great, this heat transference is very rapid; but as the charge approaches the temperature of the hot gases the rate of flow of heat is less, and there is no longer a transfer of heat when the temperatures of the charge and the gases of combustion are the same. It follows, therefore, that the gases of combustion must always leave the furnace at a temperature not less than that of the charge, and, in general,

at a much higher temperature. Hence large quantities of heat leave the furnace with these gases without doing useful work. While enormously high temperatures can be theoretically obtained by combustion of fuel in practice, these are somewhat lowered by the low proportion of oxygen in air, the nitrogen present taking up a considerable quantity of the generated heat and, of course, carrying it off from the furnace.

In the case of the electric furnace, however, conditions are different. Here the heat is derived from the electric current, and if it is generated, as it may be, in the furnace charge it will all be transferred to the charge, none being carried off wastefully as in the case of the combustion of fuel.

Suppose, for example, that a piece of platinum wire is to be melted electrically. The quantity of energy required to melt the platinum will be the calories required to raise its temperature to the melting-point, plus the calories required by the latent heat of fusion, plus the heat lost by conduction and radiation. If, now, a small current of electricity is passed through the wire the temperature will be raised, until the rate at which heat is lost balances the rate at which it is generated by the current. If, however, the current is increased so that the rate of generation of energy is increased, a point will finally be reached where the wire melts. Now it will readily be seen that if the rate of generation of energy is sufficiently increased the wire will be instantly melted, so that there is an almost inappreciable loss of energy by radiation and conduction. Consequently very nearly all the energy generated is usefully employed in melting the platinum, and the thermal efficiency of the process is nearly 100 per cent.

On the other hand, if the platinum wire is to be melted by the combustion of fuel with air, the method is bound to be very inefficient, for the melting-point of platinum is 1750° C., and by the combustion of fuel in air a maximum temperature of about 2000° C. is all that can be obtained. Hence the heating is bound to be slow, and there is very great waste as the temperature of the wire approaches its melting-point.

The limit of temperature of the electric furnace as usually employed is that of the electric arc, about 3600° C. Theoretically higher temperatures than this can be obtained by the combustion of fuel; but not, so far, in a practical way, so that the limit of temperatures practically attainable in the fuel furnace is probably below 2000° C. Hence certain products can only be obtained in the electric furnace because of the very high temperatures readily obtained in that apparatus.

Finally, quite apart from considerations as to cost of heating and to temperatures attainable, the electric furnace has the great advantage of generating heat by a method that permits of much more perfect control of the temperature and the atmosphere in which the heating is carried on than can be realised in fuel-heated furnaces.

§ (2) Types of Furnaces.—Electric furnaces for metallurgical work may be divided into two main divisions: (1) Arc Furnaces, (2) Resistance Furnaces. In the former division heat is generated by an electric arc and the various furnaces may be classed under two subdivisions, (*a*) direct arc, (*b*) indirect arc. In the case of (*a*) the arc is formed between an electrode or electrodes and the charge or material under treatment. In (*b*) the arc is formed between two or more electrodes and heats the charge by radiation. In many furnaces which are usually listed under (*a*) we actually have a combination of arc and resistance heat. This is particularly the case in so-called "smothered arc" furnaces, where the heat is generated in part by the arc and in part by the resistance of the charge. Indeed, during the actual working of the furnace the arc may at times be wholly suppressed, so that the furnace is really a resistance furnace. Division 2 may be subdivided into furnaces where the charge forms the resistor and furnaces in which the resistor is a separate substance, the heat being conveyed to the charge by radiation or conduction or convection.

The accompanying figures show in diagrams the principles of the various kinds of furnaces used in metallurgical work.

(i.) *Direct Arc Furnaces.*—In *Fig.* 1 is shown a furnace of the direct arc type. It represents

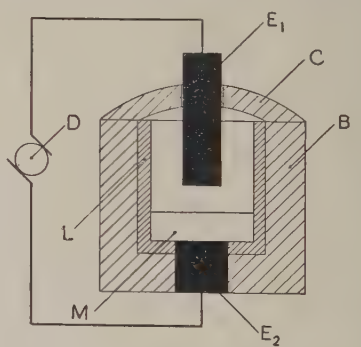

Fig. 1.

a vertical section through the furnace body B The crucible or reaction chamber containing the charge M has a refractory lining L, and a cover C. The current from the source D is brought into the furnace by the electrodes E_1 and E_2. The latter is built into the bottom of the furnace and is in contact with the charge

M; the other electrode, E_1, is movable and passes through the cover C. It can be lowered so as to make contact with the charge, and then on withdrawing an arc is formed between the charge and the electrode. It is obvious that this furnace may be constructed with two or more electrodes connected in parallel.

In *Fig.* 2 is shown another important form of direct arc furnace. Here there is no bottom

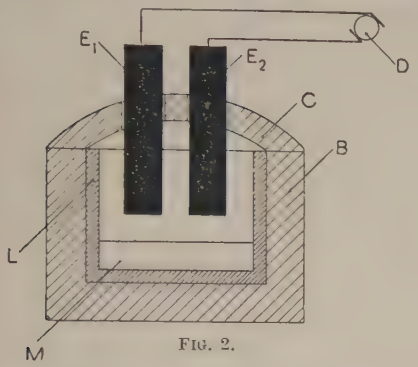

FIG. 2.

electrode, but the current is brought in by two movable electrodes E_1 and E_2 which pass through the cover C. An arc is formed between each of these and the furnace charge. A furnace of this kind is adaptable for three-phase current when three movable electrodes passing through the cover are used, one phase being connected to each electrode. In this case the transformers may be either star or delta connected. Sometimes when the star connection is used the hearth of the furnace is used to form a fourth electrode connected to the neutral of the source; but of course in such a case when the load is balanced no current flows through this electrode.

(ii.) *Indirect Arc Furnaces.* — In *Fig.* 3 is shown a vertical section of an indirect arc

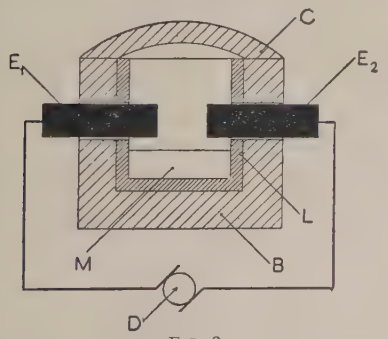

FIG. 3.

furnace. Here the arc is formed between the electrodes E_1 and E_2 and heats the charge by the radiation from the arc. This furnace may be adapted to three-phase currents by using three electrodes.

(iii.) *Resistance Furnaces.* — It is obvious that the furnace of the form shown in *Fig.* 1 may be used as a resistance furnace, for if the charge M has a high resistance the electrode E, instead of being above the charge, will be plunged in it, and the heat will be developed in the charge because of its resistance to the passage of the current.

In *Fig.* 4 is shown a vertical longitudinal section of a resistance furnace in which the

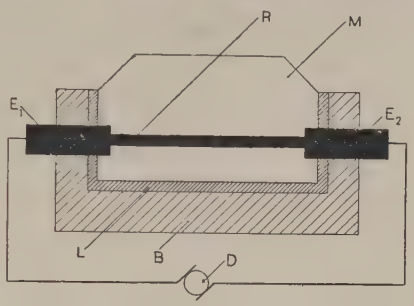

FIG. 4.

heat is mainly generated in a resistor which is not the charge itself. The body of the furnace is in the form of a box B built of brick with or without a lining L and containing the charge M. The electrodes E_1 and E_2 are built into the end walls of the furnace and are electrically connected with one another by the resistor R. The current passing through the resistor raises it to a high temperature and the heat is conveyed to the charge by conduction.

In *Fig.* 5 is shown the construction of a furnace in which the heat is generated in a

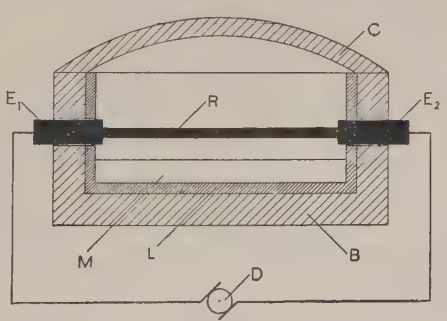

FIG. 5

resistor as in *Fig.* 4, but is conveyed to the charge by radiation from the resistor.

In all the furnaces hitherto considered the current is supplied either directly from a

generator or from transformers; but in *Fig.* 6 is shown a resistance furnace which is itself a transformer. The body B of this furnace is

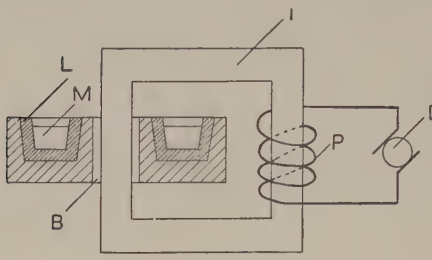

FIG. 6.

in the form of a ring composed of a refractory non-conductor and containing a trough with lining L, this trough being filled with the conducting charge M. Linked in the ring is a magnetic circuit I, and wound on this circuit is the primary coil P connected to the source of current D. Thus this furnace is a transformer in which the secondary circuit consists of the charge.

(iv.) *Pinch Effect.*—When an electric current passing through a liquid resistor exceeds a certain amount we get what has been called the "pinch phenomenon" by Hering, who describes it as follows:

"When the current density in a liquid conductor in an open channel is increased sufficiently, the conductor will be found to contract in cross-section. . . . This contraction resembles the depression in plastic material that has been pinched between the fingers . . . the writer termed it the 'pinch phenomenon' for want of a better name" (1).

If the liquid conductor is contained in a suitably arranged tube, however, the effect is to cause a strong circulation of the liquid,

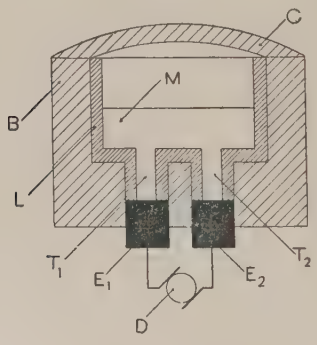

FIG. 7.

which is made use of in a furnace designed by Hering and shown diagrammatically in *Fig.* 7. Here the two electrodes E_1 and E_2 are at the bottom of two tubes T_1 and T_2 respectively, which open into the main part of the furnace containing the charge. The result of passing a current at high density through the liquid material contained in the tubes is to cause a strong rush of liquid out of the tube along the central axis, while liquid is drawn in at the peripheral part of the tube opening.

§ (3) FURNACE MATERIALS. (i.) *Refractories.*—In the construction of electric furnaces the refractory materials used for the furnace body, linings, covers, etc., are similar to those employed in metallurgical work as carried on in fuel-fired furnaces; but owing to the different construction of the furnaces the problems presented are often not the same. Owing to the very high temperatures at which electric furnaces work, the strain on refractory materials is often more severe than that in fuel furnaces; but, on the other hand, in many cases, in spite of the much higher temperatures, the refractory problem is simplified because the maximum temperatures are produced in the material which is being treated, and the lining or body of the furnace is never subjected to excessive temperatures. Fortunately, too, the electric furnace itself has produced new refractories which have proved valuable, such as silicon carbide, aluminium nitride, "alundum" (fused alumina), fused magnesia, etc.

(ii.) *Electrodes.*—An important accessory of most electric furnaces is the electrode. Electrodes in general are made of some form of carbon. The carbon electrode may be made of petroleum coke bonded with tar or pitch, moulded, and baked in a kiln. This kind of electrode is suitable up to sizes of about 6 inches in diameter, but for electrodes of greater cross-section the best raw material appears to be retort carbon or calcined anthracite coal. The anthracite is usually mixed with a certain amount of petroleum coke, and pitch is used as a binding material. Another form of carbon electrode is made of graphite. This electrode is first made of petroleum coke, as described above, and is then put in an electric furnace and heated to a temperature at which the carbon is completely converted into graphite. The graphitised electrode made in this way has a resistivity approximately 25 per cent of that of the ordinary electrode.

The electrodes of electric furnaces are connected to the source of current by means of copper usually, though occasionally aluminium busbars are used. Where the electrodes are movable, flexible copper cables are connected to the electrodes by means of suitable clamps which make contact. These, in the case of large furnaces, are frequently water-cooled. In small furnaces where the electrodes are movable the motion

is effected by hand-operated machines; but in larger furnaces these are driven by electric motors, and in many modern furnaces the regulation of the electrodes is effected automatically.

(iii.) *Transformers.* — Electric furnaces are occasionally connected directly with the generator, but generally current is supplied at high voltage and is transformed to the furnace voltage. Transformers for electric furnace work, particularly in the case of large furnaces, are of special design as they are apt to undergo very severe usage, and consequently special attention has to be paid to the bracing of the coils. Moreover, it is found that when electric furnaces of the type used, for example, in the manufacture of steel are on the same circuit with other users much trouble is found with voltage regulation, and to overcome this a high inherent reactance is necessary in the furnace transformer.

(iv.) *Voltage Regulators.* — In the case of certain furnaces of the resistance type, which require for their working constant power, it is necessary to have some means of varying the voltage at the furnace terminals so as to compensate for the variation in the resistance of the resistor. This may be done in various ways. For example, the primary coils of the transformer supplying the current to the furnace are provided with a series of taps, and, by connecting the cables from the source of high-voltage current to different taps, the ratio of transformation is changed, thus varying the voltage of the secondary coils of the transformer. The terminals of the secondary coils of the transformer are also brought out and means provided for connecting these in suitable combinations, series or parallel, so as to get different voltages on the busbars going to the furnaces.

Another method of varying the voltage is by means of induction voltage regulators. This kind of regulator is provided with a stationary primary wound in a slotted field and a secondary in the form of a drum-shaped core which can be rotated with reference to the primary. Thus, by adjusting the relative position of the coils in series and in shunt with the circuit the phase relations between the circuit voltages are varied and the voltage on the busbars of the furnace is adjusted.

Sometimes a combination of these methods is used, the voltage being varied in a series of steps by means of taps brought out from the primary of the transformer, while between steps the voltage is regulated by means of the induction regulator.

§ (4) METALLURGICAL FURNACES. — The electric furnaces used in metallurgical work present a large number of forms, so large that it would be impossible to consider nearly all of them in the limits of the present article; therefore, a few examples will be chosen for the purpose of illustrating the application of the different types of furnace described above.

(i.) *Iron Ore Reduction Furnaces.* — In reducing iron from its ores, the reducing agent is carbon, which, at high temperatures, combines with the oxygen of the iron oxide in the ore according to the following equation, which applies in the case of a hematite ore:

$$Fe_2O_3 + 3C = 2Fe + 3CO.$$

In carrying out this reaction energy is absorbed, and in the blast furnace the heat energy is supplied by the combustion of carbon. In order, therefore, to supply this energy the carbon, which must be mixed with the ore in carrying out the process, must be considerably in excess of that required for reducing the iron oxide, this excess, by its combustion in the air blast, supplying the heat energy necessary for the reaction. In the electric furnace, however, the carbon required is merely that needed for reduction plus the small amount included in the iron as graphite or iron carbide, the heat energy necessary being generated by the electric current. Pig-iron has been produced in considerable quantity in a furnace of the kind shown in *Fig.* 1 and generally known as the Siemens furnace, having been patented by him in 1879 (2). Siemens invented this furnace especially for melting metals, but it is one of the simplest electric furnaces for a great variety of metallurgical operations.

(ii.) *Héroult Furnace.* — A typical furnace for the reduction of iron ore was designed by Héroult for experiment made in 1906 for the Canadian Government in Sault Ste. Marie (3). The furnace consisted of a cylindrical casing $\frac{1}{4}$ inch thick. The casing was made in two sections each 48 inches in diameter and together giving a depth of about 70 inches. It was bolted to a circular iron plate in which were cast a number of iron rods which projected vertically inside the casing. These rods were for the purpose of making good contact with a carbon paste, made of a mixture of coke and tar or pitch which was rammed into the lower parts of the furnace, thus forming one electrode, corresponding to E_2 in *Fig.* 1. A projection from the iron plate served to make contact with one of the cables carrying the electric current. The iron casing was lined with fire-brick corresponding to B in *Fig.* 1. There was no other lining. An opening was made in the casing and the brick lining, at the level to which the carbon bottom was rammed, to serve as a tap-hole. The furnace had no cover. The 16-inch-square movable electrode (E_1, *Fig.* 2) was suspended from a truck travelling on two I beams above the furnace and provided with pulleys over which the chain suspension passed and went to a

winch by means of which the electrode could be raised or lowered.

The current for the furnace was supplied from a single-phase transformer of 225 kilowatt capacity, 2200 volt primary, 50 volt secondary.

In working this furnace the ore and coke, or charcoal and limestone, should be crushed to pieces about 1 inch diameter and mixed. The current is started with the furnace empty except for a little crushed coke in the bottom, electrode E_1 being lowered till it touches this and an arc is formed. Then the mixture is fed into the furnace until it is full. The power is regulated by raising or lowering the electrode, and as the charge sinks down in the furnace more mixture is charged and from time to time the pig-iron is tapped. There is considerable variation in the amount of energy consumed in making a ton (2240 pounds) of pig-iron in a furnace of this kind, but a fair average is 2250 kilowatt hours (3000 horse-power hours).

In modern practice this furnace is not used for the manufacture of pig-iron for various reasons, one of the most important being that it does not lend itself to large-scale working. It will readily be seen that to make a furnace of this kind of large capacity would require the use of a movable electrode of an altogether impracticable size. Nevertheless, for certain processes the furnace is of great practical importance; for example, in the manufacture of phosphorus. When phosphate rock, which is a calcium phosphate, is heated with carbon and silica, the former reduces the oxide of phosphorus and the latter combines with the lime to form a fluid slag of calcium silicate. The phosphorus is vaporised and can be drawn off and condensed. When used for this purpose the furnace has a cover and the electrode passes through a stuffing-box of some kind which makes the furnace gas-tight. Through a suitable opening the phosphorus vapour is conducted to a condenser.

It should be noted that the furnace may be either of the arc or resistance type and is sometimes described as a smothered arc furnace. Thus, when starting it is simply an arc furnace, but when it is filled with charge the end of the movable electrode is buried and the furnace may act purely as a resistance furnace in which the resistor is the molten or semi-molten charge. In the manufacture of a ferro-alloy like ferrotitanium the furnace at the start is an arc furnace; then after the furnace is fully charged it works, in part at any rate, as a resistance furnace; but before tapping it again works as an arc furnace. This is necessary because the molten ferro-titanium must be heated to an extremely high temperature in order that it may be successfully tapped.

A furnace of this type is used for the manufacture of various other materials, such as ferrochromium, calcium carbide, ferrotungsten, ferromolybdenum, etc., and in a modified form is used for the manufacture of steel; but for reasons already mentioned the design has disadvantages for furnaces of larger size. For example, in the manufacture of ferrosilicon a more suitable furnace is that shown in *Fig.* 2.

(iii.) *Ferro-silicon Furnace.* — There are two methods of making ferrosilicon: (1) a mixture of iron oxide, silica, and some form of carbon is heated in the electric furnace, the carbon reducing the iron oxide to iron and the silica to silicon, which, combining with the iron, forms ferrosilicon, (2) a mixture of scrap iron or steel, silica, and carbon is heated in the electric furnace, the silicon when reduced alloying with the iron to form ferrosilicon. Usually the second method is employed because much less electrical energy is required to melt the scrap iron or steel than to reduce iron from ore, and the costs of the energy used for reduction, labour, etc., are usually more than the cost of the scrap.

An actual furnace for the manufacture of ferrosilicon, and having a capacity of 700 kilowatts, has a steel casing of approximately elliptical form, 9 feet long and 5 feet wide, bolted to a steel plate which forms a bottom. The lining of the vertical part of the casing is silica brick and that of the bottom is a carbon paste rammed in to a thickness of about 16 inches. At the same level as the carbon bottom an opening with a spout is provided for tapping the furnace. The depth of the furnace from the top of the casing to the carbon bottom is about 32 inches. The carbon electrodes, 20 inches in diameter and 7 feet long, are suspended by cables passing over pulleys mounted on a steel framework above the furnace. The cables are brought back to winches which are run by electric motors. The ends of the electrodes are drilled to a depth of about 10 inches and threaded so that by means of threaded carbon nipples new sections of electrode may be attached and continuously fed into the furnace. The electrodes are carried by hinged, cast steel, water-cooled clamps which also serve to carry the current. The current is brought to the clamps by hollow copper pipes which also carry the cooling water. The current is carried to the copper pipes by means of flexible copper cables attached to the busbars coming from the secondary windings of the transformer.

In starting, the furnace arcs are drawn between a layer of small scrap iron on the carbon bottom of the furnace and the two electrodes, these being raised or lowered so that the power generated in each arc is the same. The voltage between electrodes is 80, hence each arc is held at 40 volts and the total power is 700 kilowatts. A mixture of

scrap iron, pure quartz or sandstone crushed to pieces about 1 to 2 inches in diameter, and coke of the same size, is fed into the furnace until it is full. The furnace then runs continuously and is tapped every two or three hours. The regulation of the power is automatic, two regulators being used for the purpose, one controlled by the current, the other by the arc voltage. The regulators automatically work contactors which cause the motors running the winches to raise or lower the electrodes.

A furnace of similar construction to this is used for the manufacture of calcium carbide, ferrochromium, and other materials. It will be observed, however, that while the furnace just described has considerable advantages over the Siemens single electrode type, it has the disadvantage of requiring a single-phase current. Most modern electric power stations supply three-phase current and the unbalancing of load caused by a single-phase furnace is objectionable. The type of furnace just described can readily be designed for three-phase current. For example, a furnace for the manufacture of ferrosilicon is constructed in the same way as that just described except that the steel casing is made larger so as to accommodate three electrodes instead of two, each of these being connected to one phase of the three-phase current supplied from delta-connected transformers. The voltage between phases is 70 volts, which gives approximately 40 volts on each arc, the furnace, of course, being in star when running normally. Furnaces up to 5000 kilowatts and even more are constructed in this way for the manufacture of ferrosilicon; but, of course, in such cases much larger electrodes than 20 inches in diameter are used, and there are modifications in holders, etc., too numerous to describe. Furnaces of this kind have also been used for the manufacture of ferromanganese, calcium carbide, etc. In the case of furnace running on three-phase current the regulation of the power is effected by preserving a constant current of the same amperage in each phase.

(iv.) *Three-phase Furnace.* — In the large modern furnaces used for pig-iron manufacture, a three-phase current is used and the construction of the furnaces is very much modified. In the first place, the furnace is of the shaft type, something like a blast furnace, but not nearly so high, the charge being fed in at the top, while the electrodes are near the bottom of the shaft and are arranged in a circle 120 degrees apart. The electrodes do not enter the furnace vertically, but at an angle to the vertical so as to clear the shaft down which the charge travels. The idea of this arrangement is to utilise the heat and the carbon monoxide gas coming from the main reaction zone, so that conditions are somewhat similar to those in a blast furnace (4). The electrical capacities of these large units are from 2000 to 7000 kilowatts.

So far as the smelting of iron ores in the electric furnace for the production of pig-iron is concerned, it is only in very special circumstances that it can compete with the blast furnace. The principal condition involved is relatively low cost of electric energy as compared with coke. A careful study made by Harbord several years ago showed that if the ratio of the cost of electric energy per horse-power year to the cost of coke per ton was as 10 to 7, then electric furnace pig-iron would cost approximately the same as the blast furnace product (5); but such great changes have taken place since that time in costs of labour and materials that these figures probably do not represent what would now be true.

On the other hand, in the manufacture of such materials as ferrosilicon containing more than 15 per cent silicon, ferrochrome, ferro-titanium, calcium carbide, and other materials made in the furnaces described, it would be either enormously expensive or altogether impossible to produce them except in the electric furnace.

(v.) *Steel Furnaces.* — While steel is a material which can be readily made in various forms of fuel-fired furnaces, the use of the electric furnace has increased enormously in recent years, not only because in many cases it is cheaper to manufacture in this way, but because of the higher quality of the product. The fuel-fired furnaces used for steel manufacture are the crucible, open hearth, and Bessemer. The crucible furnace might be described as a simple melting process, as there is little or no opportunity to refine or purify the steel. The thermal efficiency of crucible furnaces is low and the crucibles, which have a very short life, are a very serious item in the manufacturing cost. Thus it is that the crucible process is the one which finds the severest competition from the electric furnace.

In the open-hearth furnace, which has a much higher thermal efficiency than the crucible furnace, the steel is refined, but even here under certain conditions and for certain grades of steel the electric furnace has great advantages. In the first place, the thermal efficiency of the regenerative open-hearth furnaces probably does not exceed 20 to 30 per cent, while in the electric furnace efficiencies of 60 to 80 per cent and perhaps even higher can be reached. Secondly, there is a better control of refining conditions and consequently the production of a superior material.

As regards the Bessemer furnace, there is, of course, no comparison to be made as regards thermal efficiency; but the refining which can be done in the Bessemer process is limited.

Finally, it may be noted that even where the open-hearth or Bessemer process is used it is often found to be advantageous to transfer the hot metal from these to electric furnaces for final treatment.

Several of the different types of electric furnaces are used for steel manufacture. The Siemens furnace of the kind shown in *Fig.* 1 is used for steel-making, but has to be modified somewhat for that purpose. It would not be possible to use as the bottom electrode E_2 any form of carbon, for this would be taken up by the steel; accordingly the bottom is formed of magnesia made by calcining magnesite, the natural form of magnesium carbonate. This material when heated to a high temperature is a fairly good conductor of electricity and forms the lower electrode of the furnace. In the case of the Keller electric steel furnace the current, when the furnace is cold, is carried through the bottom by means of a number of steel rods which make contact with the bottom plate of the steel casing. In the Girod furnace heavy steel electrodes project from the bottom plate and pass through the magnesite lining. More than one movable electrode (E_1 in *Fig.* 1) may be used, these being, of course, connected in parallel.

The Héroult steel furnace is perhaps the most widely used of those based on the principles illustrated in *Fig.* 2. It is generally built for use with a three-phase current and consequently has three electrodes, one connected to each phase of the circuit. A description of a 15-ton furnace of this kind, as used in the South Chicago works of the United States Steel Corporation, will give an idea of this important apparatus.

The furnace rests, by means of a floating pinion riveted to its shell, on a stationary rack 8 feet 9 inches long, which is fastened to the concrete foundations raised about 5 feet above ground level. The arc of the floating pinion has a radius of 10 feet and allows the tilting of the furnace to a maximum of about 29° from the horizontal. The tilting of the furnace is effected by means of a hydraulic ram. The position of the centre of gravity is adjusted so that the furnace always tends to come back to the horizontal position.

The furnace shell is made of plates of steel, 1 inch thick, riveted together. In a plan view the shell forms a circle, 13 feet 6 inches in diameter, with flattened portions at opposite ends of a diameter passing from the front to the back. The bottom of the shell is also of steel, and the whole casing is lined with magnesite brick to a thickness of $4\frac{1}{2}$ inches in the bottom and 18 inches on the sides. The bottom of the furnace is further lined with calcined magnesite, the shape of the bottom being concave so as to form a portion of a sphere having a radius of about 7 feet. There are five doors in the furnace, two on each curved side and one on the flattened front over the pouring spout.

The roof of the furnace is held in a movable ring which has a top and bottom angle iron to carry skew-back brick from which the arch springs. Three circular holes, with their centres on the angles of an equilateral triangle, are left in the roof to permit of the introduction of the electrodes. The sides of the triangle are 5 feet 2 inches in length, and one apex points directly to the back of the furnace on a diameter through the centre line of the spout.

A steel framework attached to the back of the furnace carries the electrode holders, which are designed for electrodes 24 inches in diameter and are carried by chains which pass over pulleys to drums fastened at the back of the furnace. The drums are run by electric motors controlled by hand or an automatic regulator which keeps the current on each electrode the same, thus balancing the load.

The furnace has an electrical capacity of 2250 kilowatts and 110 volts between phases; but in modern practice when working with cold charges a higher voltage is used during the melting period, and a lower voltage during refining.

In working this furnace with hot charges molten metal from a Bessemer convertor or open-hearth furnace is poured in at the spout, a mixture of lime and iron oxide thrown into the furnace through the doors, the electrodes lowered, and the metal thus treated with an oxidising slag to remove phosphorus. When dephosphorising is complete, the furnace is tilted slightly and the slag removed with rabbles, after which a recarburising slag is used. Lime and fluorspar is added and a quantity of coke dust, which reacts with the lime forming calcium carbide. When tests show that the desired grade of steel is obtained, the furnace is tapped by tilting and pouring the metal into the ladle. A heat of this kind lasts $1\frac{1}{2}$ to 2 hours (6).

When working on cold metal the furnace is filled with scrap steel and the current started by lowering the electrodes till they make contact with the charge. It is sometimes the practice to use a higher voltage for melting than for refining, and one method of doing this is to connect the transformer primaries in delta during the melting period, and in star during the refining period.

The above description illustrates the general principles of electric steel-making with this furnace, but there are various modifications both in the methods of working and in the furnaces. For example, in the later designs by the U.S. Steel Corporation, the furnaces are tilted for pouring about an axis passing through the spout, and the tilting is done

by electric motors instead of by a hydraulic ram.

(vi.) *Induction Furnaces.* — Another important form of steel furnace depends on the principles illustrated in *Fig.* 6. This furnace was independently invented by Colby in the United States and Ferranti in England, and many years later was apparently reinvented by Kjellin in Sweden. The original furnaces were purely melting apparatus, like crucibles, no appreciable refining taking place. The furnaces were started by putting a cast-iron ring in the circular channel which is provided to contain the molten metal secondary of the transformer. This ring is then melted by the induced current and cold metal added to the molten bath thus obtained. The metal is selected to give the desired grade of steel, and when this is obtained the furnace is tilted and the molten metal cast in ingot moulds.

Electric steel furnaces working on the induction principle in which refining can be carried out have been successfully developed by Rodenhauser and others. In these furnaces, instead of using a complete ring as the secondary, part of a ring is used, the ends terminating in a reservoir which forms the main bath of molten metal. Thus in the Rochling-Rodenhauser three-phase induction furnace three half rings have their ends terminating in a central reservoir which contains the greater part of the bath of molten metal. In this, refining of steel can be carried out as in the electric furnace already described.

Obviously, a furnace of this kind is more suitable for a duplex process where molten metal is charged for refining purposes, since the starting of the furnace by melting down rings of cast metal is an expensive and troublesome process. Once, however, such a furnace is started it can be used for cold charges by leaving a certain percentage of the molten metal in the furnace when tapping, so as to provide a sufficient secondary electric circuit, and then charging cold metal.

Furnaces working on the induction principle have not been extensively used, outside of Germany; but in that country there have been very considerable developments (7).

(vii.) *Radiation Furnaces.*—Another interesting steel furnace, although one which has not been extensively used, is that of Stassano. It works on the principle illustrated in *Fig.* 3, that is, by heat radiated from an electric arc or arcs, to the charge. The furnace consists of a cylindrical steel shell lined with magnesite brick and is surmounted with a conical roof. The axis of the furnace is inclined at 7° from the vertical, about which it rotates during the heat. A three-phase alternating current, 90 volts between phases, is used with three electrodes which enter the sides of the furnace through stuffing-boxes placed 120° apart on a circumference of the furnace shell. The electrodes do not enter the furnace horizontally, but are depressed by an angle of about 15°. When thrust into the furnace the electrodes meet at a point on the axis. By suitable mechanical means the distance apart of the ends of the electrodes can be adjusted, thus regulating the power. The furnace casing is provided with a charging door.

§ (5) Furnaces for Abrasives.—An important use of the electric furnace is for the manufacture of abrasives. There are two principal kinds of abrasives produced in this way, one being made by fusing bauxite, the natural form of alumina, the other by the formation of silicon carbide.

(i.) *Bauxite.*—The former is manufactured in a furnace of the type shown in *Fig.* 2, a good example being found in the Higgins furnace for the manufacture of "alundum," one of the trade names of fused bauxite. The furnace consists of a cylindrical steel shell which rests in a ring-shaped iron channel formed in the iron base of the furnace. The cylindrical steel casing is cooled by water which is sprayed on it from a circular pipe surrounding the top end of the cylinder, and the water flowing down the shell is carried off by the ring-shaped channel in which the casing rests. The iron base of the furnace enclosed by the channel is lined with carbon, but the cylindrical steel casing is unlined. The furnace rests on a truck which runs on the ground floor of the furnace room and is charged from a platform at a level about half-way up the steel casing. The two electrodes are suspended from an overhead steel structure and are connected electrically in series.

In starting the furnace the electrodes are lowered until arcs are drawn between some granular coke in the bottom, and then calcined bauxite in the form of powder is fed in. This presently fuses and becomes an electrical conductor, more bauxite is fed into the furnace, and the electrodes raised so as to keep constant power in the furnace, and so on until the shell is completely filled. The main generation of heat probably takes place in the bath of molten bauxite connecting the two electrodes, so that the furnace is really of the resistance type. The water-cooling of the steel shell prevents the fusion of the bauxite immediately in contact with it, and thus a relatively thin layer of unfused bauxite serves as a refractory insulating lining between the molten charge and the shell. When the furnace is full the electrodes are lifted clear of it and the truck is pulled out and replaced by an empty one. The fused mass in the full furnace soon solidifies sufficiently to permit

of lifting off the cylindrical steel shell, which is made slightly conical so that this can easily be done.

This process is not purely a matter of fusing bauxite, for a considerable amount of refining is carried out in the furnace. By the mixture of a certain amount of powdered coke with the calcined bauxite, the iron oxide, silicon, and titanium contained in the crude ore are reduced during fusion, and can afterwards be separated easily in the metallic form when the solidified "pig" of fused bauxite is broken up.

Since the melting-point of bauxite is somewhere about 2000° C., this process is one which must be carried out in the electric furnace.

The further preparation of the material for the market is similar to that used in the manufacture of emery, viz. crushing, grading, and making up into wheels, hones, and other forms.

The manufacture of the other artificial abrasive, silicon carbide, is carried out in a totally different kind of furnace, that constructed on the principles illustrated in *Fig.* 4. Furnaces for the manufacture of silicon carbide, which is marketed under the trade names of "carborundum" and "crystolon," have capacities ranging from 500 to 1500 kilowatts.

(ii.) *Silicon Carbide.*—A silicon carbide furnace of 750 kilowatts capacity is in the form of a box built of brick with inside dimensions of 16 feet in length, 7 feet in width, and 5 feet 6 inches in depth. The ends of this brick box are permanent structures, and carry the terminals or electrodes of the furnace. These are made of carbon in various forms, one being a carbon electrode 24 inches in diameter built into the terminal wall and projecting a few inches from it on both sides. On the outer side it is surrounded by a water-cooled metal clamp to which the cables carrying the current are attached. The sides of the brick box are not permanent structures, but are built of loose brick, since these must be taken down, in part at least, in order to unload the furnace, for the process is discontinuous, *i.e.* the furnace is loaded, heated for a period of 36 to 40 hours, then allowed to cool down, and unloaded.

To load the furnace the side walls of loose brick are first built up and the mixture thrown in until the furnace is about half full, so that when the mixture is levelled off it reaches about half-way up the face of the electrodes inside the furnace. The mixture consists of sand, coke, sawdust, and salt. The coke is ground so as to be of approximately the same degree of fineness as the sand; the sawdust is fairly coarse, the salt in the form of fine grains. A trench about 10 inches deep and semicircular in cross-section is then formed in the mixture along the centre line of the furnace from one terminal to the other. The trench is to receive the so-called "core" of the furnace, in other words the resistor R, *Fig.* 4. The resistor is made of crushed metallurgical coke, carefully graded so that the individual grains are approximately $\frac{5}{8}$ inch in diameter. The trench is filled with this granular coke and then more added till it is heaped up to a height of about 10 inches, after which it is rounded off so as to form a resistor in the form of a cylinder about 20 inches in diameter extending from one electrode to the other. Pieces of sheet iron are set in the ends of the trench a few inches from the electrodes, so that the coke resistor is not in contact with them. The spaces thus left are filled with finely powdered coke tightly rammed into place, after which the pieces of sheet iron are withdrawn and the powdered coke makes good electrical contact between the electrodes and the resistor. More mixture is then thrown into the furnace and the core or resistor completely covered to a depth of 2 or 3 feet.

The furnace being now ready for running, the cables are connected to the electrode clamps and the current is thrown on. The granular coke resistor has when cold a high electrical resistance, hence the necessity of having some means of regulating the voltage at the furnace terminals so that constant power is maintained in the furnace. One of the means of accomplishing this, described above, is therefore used, and the range of voltage for the 750 kilowatt furnace is from 200 to 75 volts. This allows for a change of resistance from 0·053 to 0·0075 ohm, approximately, with full power at all voltages. Actually, when the furnace is built with a granular coke resistor as described, its initial resistance is so high that the full power is not obtained even with 200 volts at starting, so in practice a certain amount of coke which has been used in a previous heat, and which has a much lower resistivity than new coke, is used in the resistor in order to reduce its initial resistance.

The chemical reaction which takes place in making silicon carbide is as follows:

$$SiO_2 + 3C = SiC + 2CO.$$

Thus, soon after the current is switched on, carbon monoxide gas is generated and must be set alight. It is in order to permit the free escape of this gas that sawdust is mixed with the furnace charge, since for every 1000 pounds of silicon carbide produced 1400 pounds of carbon monoxide gas are given off.

The heat lasts for from 36 to 40 hours, when the current is cut off and the furnace allowed to cool. The loose brick side walls are then taken down about half-way and the unchanged

mixture raked off, exposing a roughly cylindrical mass of silicon carbide stretching from one electrode to the other. The outer part of this cylinder is a greenish-coloured amorphous material of somewhat variable composition. In the outermost layers it consists of silicon carbide, apparently in an amorphous form, intermingled with nearly unchanged mixture; the layers nearer to the source of heat show complete conversion to silicon carbide, but have not got the characteristic structure of crystalline silicon carbide, presenting the appearance of a green amorphous powder more or less sintered together. Inside this layer there is about 7000 pounds weight of crystalline product, varying from small needle-like crystals in the outer parts to the large, characteristic hexagonal plates near the resistor. Next the resistor is usually found a layer of graphite formed by the decomposition of silicon carbide, for when that compound is heated beyond a certain temperature it dissociates, the silicon being driven off as vapour and the carbon remaining behind as graphite, which preserves the original form of the silicon carbide crystals, thus showing that these decompose without fusion.

The use of the electric furnace for the manufacture of silicon carbide is a particularly interesting application, because from the description it will be seen that the process is one which must be carried out between definite temperature limits. Several interesting studies of the temperatures in the silicon carbide furnace have been made (8).

Determinations by Saunders (9) were made in a commercial silicon carbide furnace of 750 kilowatts capacity. A carbon tube closed at one end was built into a furnace so that it extended from the outside of the wall to the resistor, and by means of a radiation pyrometer the temperatures of a carbon disc sliding in the tube could be observed. From the investigation these results were obtained:

Formation of "fire sand" (amorphous silicon carbide) begins at . .	1600° C.
Formation of crystalline silicon carbide begins at	1840° C.
Decomposition of silicon carbide begins at	2240° C.

From these results it is seen that the limits of temperature between which crystalline silicon is formed and remains stable are comparatively close, about 400° C. difference, and that the only method of controlling the temperature in the case of a furnace of this kind is found in designing it to give the best results for the particular electrical capacity available.

(iii.) *Graphite Furnace.*—E. G. Acheson, who invented and developed the carborundum furnace, also conceived the idea of using a somewhat similar furnace for the manufacture of graphite and for graphitising electrodes. The construction of this furnace is similar to that used in making silicon carbide, and may therefore be illustrated by the same diagram (*Fig.* 4); but actually the furnace is different in principle, since the material treated is itself the resistor R, the surrounding substance M being merely intended for heat insulation.

When amorphous carbon is heated to the highest temperatures attainable in the electric furnace it is converted into graphite; and hence when electrodes, made, for example, from petroleum coke as already described, are heated to a sufficiently high temperature they are completely graphitised and, as graphite, possess certain valuable characteristics. Thus, their electrical conductivity is nearly four times as great as that of the amorphous carbon electrodes from which they were made; their resistance to oxidation when heated in an oxidising atmosphere is increased; resistance to disintegration when used as anodes in certain electrolytic processes is very much greater than that of amorphous carbon electrodes; they are so much softer than ordinary carbon electrodes that they can be machined with great ease.

The furnace for graphitising electrodes is built of various capacities from 200 kw. to 1500 kw. A 750 kw. furnace is in the form of a brick box of the same kind as that used for silicon carbide, but with inside dimensions as follows: length 30 feet, width 6 feet, depth 3 feet. The width and depth may be varied, depending upon the dimensions of the electrodes that are to be graphitised. The end walls of the furnace are permanent structures as in the silicon carbide furnace, but the electrodes built into these terminal walls are larger and square in cross-section. The bottom of the furnace is lined with "carborundum fire sand," *i.e.* the amorphous material which is found outside the crystalline zone of the silicon carbide furnace. This represents the permanent part of the furnace, for, just as in the case of the silicon carbide furnace, the side walls are built of loose brick which are taken down when the furnace is unloaded.

The method of loading the furnace depends upon the kind of electrodes that are to be graphitised. First, suppose that electrodes 2 inches in diameter and 24 inches long form the furnace charge. Then, the bottom of the furnace is first covered with a layer of finely crushed coke about 26 inches wide and 1 inch thick, extending from one end of the furnace to the other. Beginning at about 2 inches distant from one end, the electrodes to be graphitised are laid on this layer of coke with their largest dimension lying

transversely to the furnace and in close contact with one another. On top of this another row of electrodes is laid, and so on, until the pile of electrodes is about seven rows high. Pieces of sheet iron are set up along the whole length of the furnace on each side and about 1 inch distant from the pile, and the spaces between the sheet iron and the pile filled with finely ground coke. The top of the pile is also covered to a thickness of 1 inch with the coke. The side walls of the furnace are now built up, and the spaces between them and the sheet iron are filled with a mixture of sand, coke, and sawdust of the same composition as that used in making silicon carbide. The spaces between the ends of the pile of electrodes and the furnace electrodes are filled with fine coke tightly rammed in so as to make good electrical contact between the ends of the pile and the electrodes. The pieces of sheet iron are now withdrawn and the mixture of sand, coke, and sawdust thrown into the furnace so as completely to cover the pile of electrodes with a considerable thickness of mixture.

The heating of the furnace is carried out just as in the case of the silicon carbide furnace, and similar electrical apparatus must be employed to keep constant power in the furnace over a wide range of resistance. Just as in the case of the silicon carbide furnace, the resistance is at first high, but decreases, first, owing to the heating of the carbon electrodes, which have a negative temperature coefficient of electrical resistivity, and second, owing to the conversion of the amorphous carbon into graphite. After the resistance of the furnace becomes constant the graphitisation is complete, the furnace is disconnected and allowed to cool down.

When the furnace is unloaded the general appearance is the same as in the case of the silicon carbide furnace. The unchanged mixture is first removed, exposing a layer of the greenish "fire sand," underneath which is found the crystalline substance. Next the pile of electrodes the silicon carbide formed during the earlier parts of the heat is converted into graphite, and the electrodes with their surrounding jacket of finely ground coke are completely graphitised.

In the furnace just described the generation of heat by the passage of the electric current occurs nearly altogether at the points of contact of the individual electrodes where the electrical resistance is relatively high, and not in the electrodes themselves. The total area of contact is of course small, consisting as it does at most of six elements of the cylindrical surface of each electrode.

In dealing with electrodes of square or rectangular cross-section the furnace must be loaded in a somewhat different manner, as these will not give a uniform and constant contact as in the case of electrodes of circular cross-section. Suppose, then, it is required to graphitise electrodes 24 inches long, 6 inches wide, and $\frac{1}{2}$ inch thick. As before, the layer of coke is laid on the bottom of the furnace, and on this the electrodes are laid in separate piles, each pile consisting of about 25 electrodes laid one on top of the other and separated from adjacent piles by a space of 1 inch. When the pieces of sheet iron are set up the finely ground coke is filled in, not only between these and the ends of the electrodes, but also between the piles themselves. The rest of the loading of the furnace is as before. In this case nearly all of the heat is generated by the current in the powdered coke between the electrodes, this having a very much higher resistivity than the electrodes themselves.

In making bulk graphite from such materials as anthracite coal and petroleum coke, the bottom of the furnace is formed as before of silicon carbide, but the sides are permanent and are lined with silicon carbide so as to form a trench of rectangular cross-section between the furnace electrodes. This is filled with granular anthracite or petroleum coke according to the kind of graphite it is desired to make. Both of these materials have an extremely high resistivity, and therefore through the centre of the furnace charge a starting resistor is formed by a row of overlapping carbon plates extending from one furnace electrode to the other. The charge is covered with the sand, coke, and sawdust mixture. When the current is switched on, it at first is virtually confined to the starting resistor, the heat conducted from which graphitises the surrounding layers of coal or coke, and these then become conductors, and so on till the whole mass is heated to the temperature of complete graphitisation. When cooled somewhat, the furnace is unloaded by taking off the unchanged mixture and the silicon carbide that has been formed, and then removing the graphitised material.

§ (6) Zinc Furnace. — The production of zinc in the electric furnace has always been a very attractive field for experiment, because the standard methods of manufacture in zinc retorts are relatively inefficient from a thermal point of view, and retort replacements, labour, etc., involve very considerable expense. In the ordinary method of smelting the carbonate or sulphide ores of zinc are first roasted, then mixed with a carbonaceous material such as coal and heated in muffles or retorts, thus reducing the zinc, which is driven off as vapour and collected in condensers. The retorts or muffles are heated externally by coal or gas, and the temperature which the charge must reach is probably over 1200° C., so that the life of the retorts is not long. Moreover,

according to Richards, the thermal efficiency of the process is only 6·8 per cent (10). While this is, no doubt, a lower efficiency than may be obtained with better furnace design, yet any retort process must have a far lower thermal efficiency than can be obtained in an electric furnace.

It would be impossible to review all the electric furnaces for zinc manufacture that have been proposed or actually tried commercially, for this would take altogether too much space. However, it may be said that most of the types of furnace already described have been used or proposed, even including the induction furnace. De Laval met with considerable success in Trollhättan, Sweden, with a modification of the radiation arc furnace (*Fig.* 3); but his furnaces were later replaced by those of the Siemens type (*Fig.* 1), and the manufacture of zinc in the electric furnace on the largest scale has probably been carried out in this way.

Another furnace designed for zinc manufacture may be considered in more detail, not because it has been used on a large scale, but for the purpose of illustrating another type of furnace depending upon the radiation of heat from a resistor. A. H. Imbert proposed to make zinc directly from zinc sulphide ores by heating these in contact with iron according to the following equation:

$$ZnS + Fe = FeS + Zn.$$

An electric furnace was designed for carrying out this process worked on the principle shown in *Fig.* 5, and subsequently was modified considerably in order to be used for distilling zinc from impure scrap. The furnace consists of a closed, nearly cubical, brick box the inside dimensions of which are $40 \times 40 \times 36$ inches, approximately. The heat is generated in two graphitised carbon resistors which span a shallow tank in the bottom of the brick box. The resistors, made of graphite slabs having a cross-section of 8×2 inches, are slotted alternately on either side so as to form a grid. This makes the effective length of the electrical circuit formed by the resistors about 18 feet and its cross-section $3\frac{3}{4}$ square inches. The electrodes are at the same end of the furnace and to each is connected an end of one resistor, the other ends terminating in a graphite bar which serves to connect the resistors electrically in series. The furnace is provided with an inclined tube for charging with molten zinc, the end of the tube in the furnace being submerged in the bath. The furnace is also provided with a tap-hole for drawing off the contents when desired. In the upper part of the furnace beneath the roof is an opening which can be connected with the condenser. A furnace of the kind described working on 50 volts takes a current of approximately 1000 amperes and distils zinc at the rate of about 100 pounds per hour. The zinc thus distilled is pure; foreign substances such as lead and iron remaining behind are drawn off by the tap-hole from time to time.

While in this process of distilling zinc for purification purposes there is, with proper precautions, no trouble whatever in recovering the zinc by condensation in liquid form; this has proved one of the most serious problems in all the attempts at zinc-smelting, for the tendency always has been to produce an excess of "blue powder."

§ (7) Furnaces for Brass.—Another furnace design depending on the radiation of heat from a resistor has been developed by Bailey and seems to have met with considerable success in the United States. In this furnace the resistor, being composed of granular coke or carbon of some kind, obviously cannot be suspended above the charge, but is contained in a shallow trough or troughs. Spanning the troughs and the part of the furnace containing the charge, whatever that may be, is an arch which serves to reflect the heat radiated from the resistors on the charge. Naturally a certain amount of heat is also carried to the charge by conduction. Bailey's furnaces are used for various purposes, one of these, for example, being for brass-melting. In this case the furnace consists of a cylindrical steel shell supported by trunnions so that it can be tilted. The steel shell is lined and covered with an arched roof of refractory material. The bottom of the furnace is bowl-shaped. The resistor consists of granular carbon contained in a circular trough made of silicon carbide; the electrodes are diametrically opposite one another and, protruding into the circular trough, make contact with the resistor carbon. The furnace shell has a diameter of 7 feet, a capacity of 1500 pounds of brass, and working at 105 kilowatts melts about 600 pounds of brass per hour.

A furnace working on somewhat similar principles has been designed for brass-melting by the General Electric Co. (U.S.A.). It consists of a tank, on two opposite sides of which are troughs filled with granular carbon serving as resistors. Four electrodes are used, one at each end of the troughs. These electrodes are movable in a vertical sense, and are plunged in the granular carbon resistor. The troughs and tank are spanned by an arched roof which reflects the heat generated in the resistors on the metal contained in the tank. The heat is not generated merely by the passage of the current through the resistor, but also by the smothered arcs formed at the ends of the four electrodes. The power used in the furnace can be regulated by raising or lowering the electrodes.

The most extensive developments in brass-melting furnaces are found in the use of a modified form of the radiation arc furnace (*Fig.* 3), and in a combination of the induction furnace (*Fig.* 6) and the Hering "pinch effect" furnace (*Fig.* 7).

The development of the radiation arc furnace for brass-melting is due mainly to the work of H. W. Gillett of the United States Bureau of Mines. Most of the attempts made to melt brass or copper in furnaces of the types shown in *Figs.* 1 and 2 have not been satisfactory because of the difficulty of avoiding serious vaporisation of the metals. Experiments with an ordinary radiation arc furnace (*Fig.* 3) showed apparently serious zinc losses when working with yellow brass. In a modified form designed by Rennerfelt, using two-phase current with three electrodes, satisfactory results were obtained with certain bronzes not high in zinc; but where the content of this metal is high the losses are serious.

The furnace developed by Gillett is a single phase arc radiation furnace. The shell consists of a horizontal steel drum, the length of which is approximately the same as the diameter. Surrounding each end of the drum are rings which form tracks and gears. The tracks run on rollers, the gears engage with pinions turned by a motor so that the cylinder may be rocked about its axis. A graphitised carbon electrode passes through a stuffing-box in the centre of each end of the drum. The steel shell is lined first with a good heat-insulating brick, and inside that with a refractory brick. A door for charging and tapping the furnace is provided in the side of the drum. In working the furnace an arc at 120 volts is drawn between the electrodes, and the furnace is rocked back and forth through an angle of about 80° after the furnace has been under heat for some time and the charge of brass has already partly melted. As soon as most of the charge is melted the rocking angle is increased to 200°. The time of a complete oscillation at 80° is about 13 seconds, at 200° is 33 seconds. The object of the rocking is to bring the molten metal in contact with heated parts of the lining and thus prevent overheating and consequent loss of metal by vaporisation, also to mix the metal thoroughly. The furnace is tapped by opening the door and rocking to a position where it is completely emptied.

A modification of this furnace is designed with doors in the ends instead of in the side, the electrodes passing through the stuffing-boxes in the doors. This furnace, instead of rocking through an angle of 200°, rotates continuously, and the tap-hole is in one of the ends.

The furnaces of this type have high thermal efficiency, for with continuous working they use about 250 kilowatt hours per ton (2000 pounds) of metal, and the metal losses are very low.

The Hering furnace working on the "pinch effect" principle (*Fig.* 7) was tried out very thoroughly for brass-melting; but the results were not satisfactory because of the very considerable heat losses from the electrodes. These were of necessity water-cooled, and the cooling water carried off a very considerable percentage of the total heat generated in the furnace. Mechanical troubles of various kinds were also experienced. This led to the development of a furnace in which electrodes are eliminated by connecting the two tubes in which the pinch effect occurs so as to form a loop filled with molten metal, this loop forming the secondary of a transformer as in the induction furnace (*Fig.* 6), except that in this case the molten metal, instead of filling a horizontal trough, is contained in a vertical V-shaped tube with its ends opening into the bottom of the bath M (*Fig.* 7).

The ordinary induction furnace cannot be used for brass- or copper-melting because the very low resistivity of these metals involves the use of such a high current density, in order to get the required power in the furnace, that the pinch effect occurs and the molten metallic circuit is broken.

This induction pinch-effect furnace gives a high thermal efficiency, as might be expected, since the heat energy is generated in the metal; but the objection to its use is the necessity of filling the furnace with molten metal before it can be started. Nevertheless these furnaces are being widely and successfully used for brass-melting in small units of 200 or 600 pounds capacity. Their use for large units is apt to be objectionable because of the low power factor of the electric circuit.

§ (8) The Northrup Furnace. — An electric furnace of relatively recent development is the induction apparatus of Northrup, and although this has so far not had a wide commercial use, yet as an example of applied physics it is of great interest. In Northrup's furnace "heating is obtained by inducing, with comparatively high frequency currents in an inductor coil which surrounds the crucible, very large currents in the walls of the crucible or in its contents, if these are electrically conducting. The induction is obtained by electromagnetic induction without the use of any iron. The furnace differs radically from all other types of induction furnace by the entire absence of any interlinkage of a magnetic with an electric circuit. The necessary high frequency of the inducing current may be obtained in more ways than one. The simplest and most obvious method is to employ oscillatory currents obtained from the discharge of

condensers. The oscillatory currents pass through an inductor coil of about fifty turns which surrounds the crucible, and sufficiently separated from it to permit of both electrical and heat insulation. We thus have in effect a Tesla coil arrangement in which the voltage is transformed down and the current transformed up. It is to be noted that when a condenser of capacity C is charged to voltage V, energy is stored in the dielectric in potential form and in amount $CV^2/2$. When the condenser is discharged the potential energy is released and, becoming kinetic, may take the form of electric radiation as utilised in radio practice, or it may take the form of thermal energy or heat. When this principle is once recognised, it becomes purely a question of design and engineering practice so to construct apparatus and select conditions that very little energy is spent in radiation and a large percentage of the energy is converted into heat within a crucible and its contents—the necessity of the interlinkage of an iron magnetic circuit with an electric circuit being entirely obviated" (11).

The apparatus used in a furnace of this kind consists of a 60-cycle transformer, 220 volts primary, 8000 volts secondary. In the primary circuit shunt and series reactors are used. The leads from the secondary of the transformer are first connected to the terminals of a condenser, then one passes directly to one terminal of the inductor coil surrounding the crucible, the second lead to a discharge gap, the other side of the discharge gap being connected to the second terminal of the inductor coil.

A special form of discharge gap is used. In the case of the ordinary discharge gap the voltage of the secondary circuit builds up until it reaches a certain value at which the gap ruptures and the condenser discharges through it. If the impedance of the circuit is sufficiently great, then there is an oscillatory discharge. When, however, the discharge occurs through the gap, an arc tends to form which ionises the dielectric in the gap and makes it such a good electrical conductor that there is little or no rise in voltage across the gap and no continuous series of oscillations is effected. There are various methods of overcoming this difficulty, but the method actually employed depends upon the curious "negative electrode resistance" of mercury. A bath of mercury is contained in a closed vessel through the cover of which pass two electrodes with graphitised carbon tips, each of these forming a gap between it and the mercury bath. The lead from the condenser is attached to one of these electrodes, while the other electrode is attached to the inductor coil. No matter in which direction the current in the secondary circuit of the transformer is flowing, in one of the gaps between the graphitised electrode tips and the mercury the current will be flowing from mercury to an electrode tip, and it is found that when the voltage between one of these reaches a certain minimum the negative electrode resistance of the mercury opens the circuit completely and very suddenly. The action of the gap is greatly improved by working in an atmosphere of alcohol vapour, so means for keeping such an atmosphere in the discharge gap are provided.

The inductor coil in the furnace under consideration has 52 turns and an outside diameter of 7½ inches. A quartz cylinder insulates the inductor coil from the crucible, which is 5½ inches outside diameter.

There are many modifications in the construction of this furnace and the apparatus connected with it, such as water-cooled inductors, design for two-phase current, the use of what has been named a "focus inductor." This inductor consists of a coil of a single turn, and hence has a current capacity about 50 times greater than the primary inductor. It has the effect of focussing the electromagnetic field upon the mass to be heated and separates the primary inductor coil from the crucible, thus guarding the worker on the furnace from contact with all high voltage parts. A very complete discussion of the theory of this furnace and its practical application may be found in the *Transactions of the American Electrochemical Society*, xxxv. 69 *et seq.*

The limitation at the present time to the use of this form of induction furnace is the great expense involved in the electrical apparatus needed for the production of oscillatory currents of high wattage. So far developments have reached capacities of the order of 60 kilowatts; but the cost per kilowatt capacity is extremely high.

The advantages of the furnace are the high thermal efficiency which can be obtained; the ease with which materials can be melted without any contamination with carbon, which is almost inevitable to greater or less extent in furnaces where carbon electrodes or carbon resistors are used; the relative ease with which the furnace lends itself to carrying on high temperature work in a vacuum.

As regards thermal efficiency: Northrup made experiments with an Alexanderson alternator, 25,000 cycles per second and 200 kilowatts capacity supplying a furnace which was found to melt copper in quantities at the rate of 8·38 pounds per kilowatt hour.

§ (9) Furnaces for Glass-making. — The idea of using electric furnaces for glass-melting has for many years been a very attractive one; but it has not been developed to any great extent owing to the difficulty of avoiding the reducing effect of carbon on the constituents of the glass. This difficulty,

however, does not occur with the high frequency induction furnace, for glass has been very successfully melted in it. The furnace also has been successfully used for the melting of platinum.

§ (10) Production of Aluminium. — In works dealing with electric furnaces it is a common custom to include the description of the manufacture of aluminium; but the process more properly comes under the heading of electrolysis although it is partly electrothermic, since the electrolyte is kept in molten state by the heat generated by the electric current. Aluminium can be reduced by carbon from its oxide in the electric furnace; but the product is very impure, containing always a quantity of aluminium carbide. On the other hand, alloys of aluminium with copper can be made by direct reduction in the electric furnace. To do this the alumina is reduced in the presence of copper, which apparently alloys with the aluminium as fast as it is formed. This is one of the oldest electric furnace processes, having been patented by Cowles in 1884. The furnace charge acts as the resistor.

While the regular manufacture of aluminium is properly electrolytic, there have been interesting developments in the application of the electric furnace to the preparation of the raw material, alumina, used in the electrolyte. Bauxite, the source of the alumina, must be purified before it can be used in the electrolytic cells. This is done by chemical treatment which produces pure alumina, but various electric furnace processes have been devised for producing that material. Some of these processes depend upon the fusion of impure bauxite in the electric furnace with the addition of carbon in sufficient quantity to reduce the impurities such as iron, silicon, titanium, etc., to the metallic form. Thus the product of the furnace will be mainly a metallic alloy of the impurities and alumina, of course the last being in large excess. But the most interesting process theoretically is that of Serpek. In this case impure bauxite is mixed with carbon and the mixture heated in an electric furnace in an atmosphere of nitrogen, so that a reaction occurs which may be represented by the following equation:

$$Al_2O_3 + 3C + 2N = 2AlN + 3CO.$$

The aluminium nitride thus formed is decomposed by water with the formation of alumina and ammonia as follows:

$$2AlN + 3H_2O = Al_2O_3 + 2NH_3.$$

Thus in the preparation of alumina from bauxite the valuable by-product ammonia is produced. In actual practice the nitride is treated with caustic soda. Apparently one of the principal difficulties in the process is the design of a really satisfactory electric furnace for carrying out the work.

§ (11) Production of Cyanamide. — An important application of the electric furnace is found in the manufacture of calcium cyanamide or nitrolime. In making this material calcium carbide is first made in an electric furnace and is then ground to a powder, when it is ready for the nitrifying furnaces. The reaction which occurs when calcium carbide is heated with nitrogen is as follows:

$$CaC_2 + N_2 = CaCN_2 + C.$$

This is a reversible reaction. Thus, for example, when the powdered carbide contains about 82 per cent of pure calcium carbide, if the temperature rises above 1360° C., the calcium cyanamide formed is decomposed, forming calcium carbide and setting free nitrogen. Now, although it is necessary to heat the calcium carbide in the nitrogen in order to cause the reaction which produces the cyanamide, yet that reaction itself is accompanied by an evolution of heat; hence when the reaction is proceeding it is necessary to carry off the heat generated in order to avoid the reversal of the reaction. Electrical heating of the calcium carbide is therefore used, the type of furnace being that illustrated in *Fig.* 4, in which the heating resistors are carbon rods passing through the charge. The furnaces, of course, are gas-tight and are supplied with a current of nitrogen gas. The power in the furnaces is adjusted so that a temperature of 800° to 1000° C. is reached, which starts nitrification; this generates heat, and then the power must be cut off altogether or adjusted so that the temperature of the charge does not reach a point where reversal of the nitrification reaction takes place.

In recent years there has been a great increase in the use of electric furnaces for the heat treatment of metals. Under some conditions this is advantageous merely from the point of view of cost of heat; but probably the determining factor is found in the very perfect control of temperature and in the saving which may be effected on the whole cost of the work even though the cost of the heat generated electrically is higher than that obtained from the combustion of fuel. Furnaces for heat treatment of metals are usually of the resistor type. In some cases for higher temperature work on a large scale granular carbon resistors are used. In other cases metallic resistors usually are made of the nickel-chromium alloy called "nichrome."

F. A. J. F.

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9. *Transactions American Electrochemical Society*, 1912, xxi. 425 *et seq.*

10. *Metallurgical Calculations* (1906), part i. p. 80.

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The evolution of the electric furnace is proceeding so rapidly that while there are definite types of furnaces to which the various species may be referred, these show great variation. Books dealing with electric furnaces rapidly become out of date in many parts, and consequently the best information is to be found in current engineering and chemical periodicals and in the transactions of technical societies. The following references will be found useful:

Le Four électrique, par M. Henri Moissan (Paris). English translation, *The Electric Furnace*, translated by A. T. de Mouilpied (Arnold, London). This book describes the classical work of Moissan on electric furnaces.

Electric Smelting and Refining, translation of Borcher's *Elektro-Metallurgie*, by Walter G. M'Millan (Griffin, London).

Electric Furnaces, translation of Borcher's *Die elektrischen Öfen*, by Henry G. Solomon (Longman, Green & Co., London).

The Electric Furnace, by Alfred Stansfield, second edition (McGraw-Hill, New York).

Covers the history, theory, and practice of the electric furnace.

Electric Furnaces in the Iron and Steel Industry, by W. Rodenhauser and I. Schoenawa, translated by C. H. Vom Baur (Wiley, New York; Chapman & Hall, London).

"The Electric Furnaces as applied to Metallurgy." A reading list, 1900–1919, by Clarence Jay West, *Transactions American Electrochemical Society*, 1920, xxxvii. This list is a very extensive reference to the periodical literature of the Electric Furnace as applied to Metallurgy.

The Electric Furnace, by J. N. Pring (Longmans, Green & Co.).

FURNACES, ELECTRIC, for metallurgical investigations. See "Metals, Thermal Study of," § (2).

FURNACES FOR LABORATORY USE

THE selection of a furnace for use in the laboratory is largely determined by the source of energy available and the conditions of supply. With the advance in the technique of the construction of small electric furnaces, the use of electrical energy, although less efficient as a source of heat units, offers such advantages over gaseous or liquid fuels that the electric furnace has displaced other types in almost all laboratory operations where precise temperature control is desired. The variation in the pressure and calorific value of the gas drawn from town mains contributes largely to the popularity of the electric furnace, which, at any rate for work below 1000° C., possesses the advantages of portability, freedom from contaminating gases, ease of control, and uniform distribution of temperature.

The uses for furnaces in the laboratory are so many and so varied that many types have been developed to meet special needs. The construction of a small furnace for laboratory work is so easy that it is generally more convenient to design a furnace suitable for the exact requirements of the worker, and to assemble it in the laboratory, than to adapt apparatus to a standard type of furnace.

The following is a brief description of the principal types of furnaces in use, and an account of some devices which are employed to obtain special conditions or regulation of temperature.

§ (1) RESISTANCE FURNACES.—For work in which extreme temperatures are not required and in which small quantities of material are to be treated, wire-wound electric resistance furnaces are in general use. The construction of these furnaces is a simple matter, the essentials being a refractory or metal tube which is tightly wound with wire or riband of suitable dimensions to give a total resistance such that the maximum temperature desired can be obtained with the voltage available. The winding is embedded in material having a low thermal conductivity —such as light magnesia or diatomaceous earth—and the whole may be contained in a sheet-metal cylinder. Convenient thermal insulating material can be obtained in the form of pressed magnesia-asbestos cylinders, which are supplied in various diameters and thicknesses, and can easily be cut to the required length.

The efficiency of the furnace depends on the thickness of the "lagging" employed. Using a light magnesia packing, of the type mentioned above, say 5 inches thick, round a winding 15 inches long, a temperature of about 1000° C. may be obtained in a tube $\frac{3}{4}$-inch bore over a length of 4 inches with a consumption of 1000 watts.

Without special precautions to counteract the heat losses at the ends of the furnace, the length of tube over which a reasonably uniform temperature (± 2 per cent) can be obtained will be approximately a third to a quarter of the total length of the winding. This relation will only hold if the length of tube wound exceeds six times the diameter of the tube.

If the lagging is reduced, a more uniform temperature gradient is obtained, with a corresponding loss in efficiency. The thicker the lagging the longer the time the furnace takes to reach its maximum temperature.

For temperatures not much exceeding

1000° C., wire or riband made from a nickel-chromium-iron alloy [1] gives good service (these alloys are obtainable under the trade names of "Nichrome," "Chronic," etc.). Recently a wire which is said to give an appreciably longer life than those hitherto obtainable has been put on the market. The alloy has a composition somewhat similar to those mentioned above but is free from iron. These alloys have a high specific resistance (of the order of 90×10^{-6}).

Over 1000° C. the rate of oxidation becomes considerable, but can be retarded to some extent by coating the winding with alumina, bonded with a small quantity of kaolin, and surrounding the whole with a half-inch layer of powdered graphite.

For furnace winding wire gives a longer life at high temperatures than riband.

When making up a new furnace it is advisable to use the thickest wire admissible if the furnace is required for use at high temperatures, or, in other words, the lowest voltage practicable should always be used. The thickness and length of the wire required may easily be calculated from the data given in the makers' catalogues. For example, if it is required to make up a furnace with a $\frac{3}{4}$-inch bore tube, 15 inches long, to take 1000 watts, and the voltage available is 100, then the current used will be 10 amps. and the resistance of the furnace 10 ohms. Referring to a catalogue of Chronic wire we find that 10 ohms is approximately the resistance of

100 yd. of 10 S.W.G. wire,
50 „ 13 S.W.G. wire,
13 „ 18 S.W.G. wire,
9 „ 19 S.W.G. wire.

Assuming we can wind 8 turns of wire to the inch, then the total length of wire required will be 10 yd. —120 turns, 3 inches per turn; 19 S.W.G. must therefore be used. If, however, it were found possible to wind 10 turns to the inch, then 12·5 yd. of wire would be required, and we could therefore use 18 S.W.G., which would be an advantage.

For work at higher temperatures wire or strip made from platinum or an alloy of platinum and rhodium should be used.

(Where air can be excluded entirely from the furnace, tungsten and molybdenum wire may be used for the winding, but, owing to the excessive brittleness of the wires when in use, these metals are unsatisfactory for the purpose. Of the two, molybdenum gives rather better results than tungsten.[2])

Since the life of the furnace depends on the temperature of the wire during use, it is desirable for high temperature work to arrange that the tube on which the wire is wound is as thin as practicable and made from a material having a high thermal conductivity. It is also desirable that the furnace be well "lagged." A longer life may be obtained if the wire is wound on the inside of the furnace tube. This may be effected by first winding the wire on to a wooden mandrel, of a suitable size, covered with paper. The winding is then covered with Alundum cement moistened with a solution of sodium silicate and shaped with a moulding tool so that it will just fit into the furnace tube. When thoroughly dry the mandrel may be withdrawn and the winding inserted in the furnace. The temperature should be raised slowly for the first run.

Still higher temperatures (within about 30° C. of the melting-point of the wire used for the winding) may be obtained by winding on the "cascade" principle. In these furnaces two concentric heating coils are employed. For a one-inch bore furnace the tube is wound with platinum or platinum-rhodium wire in the ordinary way. This winding is placed inside a tube, 3 or 4 inches in diameter, also wound with platinum wire, the space between the tubes being packed with magnesia. In operating the furnace the temperature is first raised to about 1450° C. by passing a current through the outer winding only. This current is then kept constant and the additional temperature obtained by passing a suitable current through the inner winding. By this means temperatures exceeding 1720° C. may be maintained in the furnace with platinum-rhodium windings.

Uniformity of Temperature. — For many purposes, gas thermometry, fine annealing of large specimens, measurements of physical properties at high temperatures, and so on, it is essential to obtain uniformity of temperature throughout the furnace. An even distribution of temperature in a small specimen can be obtained merely by making the furnace large enough, but when larger specimens have to be used this becomes inconvenient. By cutting down the lagging, the heat losses at the ends of the tubes become of less importance. The furnace is then, however, more susceptible to changes of temperature in its surroundings. It is therefore best to secure that the thermal insulation be amply sufficient to damp out the effect of draughts and changes of room temperature and to take other precautions to compensate for the end effect. The insulation should be built up of alternate layers of materials having a high and low conductivity respectively, arranged parallel to the desired isothermal surfaces. Thus, the furnace winding should be insulated by coaxial metal cylinders, the space between them being packed with a good insulator, light magnesia or kieselguhr. To counteract the end effect, stoppers should be constructed on the same lines. *Fig.* 1 shows a diagrammatical section through such a stopper. It consists of discs of iron separated by light magnesia packing, contained in a refractory tube. This stopper is a good conductor of heat in the direction C-D and an insulator along its axis AB. Compensation may be made for the heat losses at the ends of the furnace by crowding the turns of wire, and thus increasing the resistance, at the ends of the winding. It is

[1] See "Alloys, Some Special," § (2).
[2] W. E. Ruder, *Trans. American Institute Mining Engineers*, 1918, lix.; Winne and Dantzigen, *Trans. Am. Electrochem. Soc.*, 1911, xx.

possible by this means (supplemented by the method of insulation described above) to obtain a high degree of uniformity of tempera-

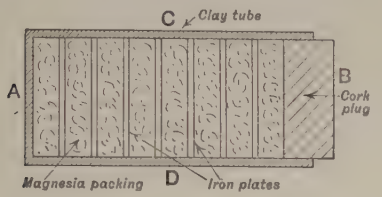

FIG. 1.

ture ($\pm 0{\cdot}5°$ C. or less) at any one temperature. Such a furnace will not, however, be uniform if used at a temperature different from that for which it was compensated, being under-compensated for a higher and over-compensated for a lower temperature. To construct a furnace to give uniformity at all temperatures it is necessary to use a number of separately controlled windings. *Fig.* 2 shows a diagrammatic section through such a furnace. It is necessary to have B and C separately controlled, since, in practice, it is impossible to make the ends exactly similar. Generally speaking, it

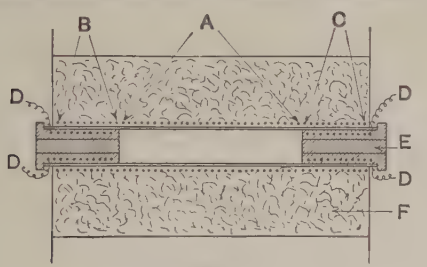

FIG. 2.

A, Central uniform winding; B and C, supplementary windings; D, windings in stoppers; E, clay stopper; F, light magnesia packing.

is easier to obtain uniformity in a tube mounted horizontally than when mounted vertically.

With a little patience in adjustment, a furnace built on the lines described above can be run at any temperature with a maximum temperature variation of the order of $0{\cdot}2°$ C.[1]

§ (2) GRADIENT AND TUBE FURNACES.—Rosenhain describes a gradient furnace constructed to give a steady rise of temperature along the tube from 200° C. to 1000° C. The furnace, which is mounted vertically, consists of a refractory tube, 2 feet long, wound with "Nichrome" wire on the top 6 inches of the tube only, the lower part of the tube being heated by radiation and conduction only. The bottom may be water-cooled.[2]

[1] Ferguson and Merwin, *Am. J. Sci.* xlvi.
[2] Rosenhain, *Inst. of Metals J.*, 1915, No. 1.

It is found that a remarkably even gradient is produced. The use of a metal tube instead of a "refractory" tube gives a longer range of steady gradient (down to about 40° C.); iron may be used for low temperatures, and tubes made from a heat-resisting alloy are now obtainable for higher temperatures. It is necessary that the furnace be sealed at one end, to prevent draughts and convection currents. These furnaces are practically indispensable for investigations of the constitution of systems of alloys, etc., by thermal methods.

For temperatures up to 1000° C. fused silica provides almost an ideal furnace tube. The resistance of these tubes to sudden changes of temperature is remarkable. Cold water can be swilled through a furnace running at 1000° C. without fear of fracture if suitable precautions are taken to avoid the production of high pressures through the generation of steam. This property of fused silica is utilised in a furnace designed for chilling metal specimens rapidly from high temperatures. One end of the silica tube of the furnace is connected to a filtering flask which can be evacuated when desired. The other end of the tube is attached to a wide bore tap leading to a tube, the end of which is immersed in a basin of water. The tap is first turned off and the flask evacuated. When the specimen reaches the desired temperature the tap is turned on and the cold water rushes through the furnace, washing the specimen into the flask.[3]

Above 1000° C. silica begins to crystallise, forming trydimite at an appreciable rate. The tube, after a time, becomes brittle. However, reasonable service can be obtained from silica up to 1200° C.

Above 1200° C. hard fired porcelain tubes, rich in alumina, can be used up to 1500° C. For temperatures up to 1750° C. tubes made from alumina-clay mixtures are serviceable. So-called "alumina" tubes must, however, be used with caution, since they are liable to sag in use at comparatively low temperatures (1350° C.), unless special precautions in the choice of binder and firing temperature have been taken in the manufacture. (See "Refractories," § (37).)

For temperatures above 1700° C. other types of furnaces are employed. Where a strongly oxidising atmosphere is essential the iridium tube furnace is useful for temperatures up to 2000° C. The high cost of the tube generally limits the furnace to small dimensions. The iridium tube is usually mounted with platinum flanges to which silver leads are attached. The resistance of a tube 2 cm. bore (thickness of wall about 0·25 mm.) and 15 cm. long is about 1/100 ohm.

[3] Rosenhain, *Iron and Steel Inst. J.*, 1908, i.

With suitable thermal insulation, a temperature of 2000° C. may be reached in such a tube with a consumption of about 3000 watts.

Harker developed a type of furnace which is capable of considerable extension. He used for his heating element a tube composed of a mixture of oxides of rare earths, chiefly zirconia, of a composition similar to the well-known Nernst filament glowers. The furnace is built up on the cascade principle (see § (1)), the outer heating unit being a porcelain tube, about 4 cm. diameter, wound with nickel wire. Inside this was placed a tube made from the rare earth oxides, the space between the two tubes being filled with pure zirconia. The current was supplied to the central tube by platinum wires wound round the ends of it. For the smallest size of furnace—1 cm. bore, 7 cm. in length—tubes of uniform thickness were used, but for larger sizes, where some difficulty was experienced in preventing the junction of the zirconia and the platinum wire from becoming overheated, the tubes were constructed with thickened ends. Owing to the large negative temperature coefficient of resistance of the zirconia tube, a resistance must be introduced in series with it. If the temperature of the nickel winding is maintained at 1000° C. the inner tube (1 cm. bore) may be brought to 2000° C. with a consumption of 200 watts (2 amps. 100 volts), the external resistance in series being 10-12 ohms. The temperature control between 800° C. and 2000° C., by means of a regulating resistance, was easy and accurate.[1]

§ (3) Graphite or Carbon Resistance Furnaces.—Many types of furnaces using carbon or graphite as the heating element are in use and have been described. These may be summarised under the following heads :

(i.) Carbon or graphite tubes.
(ii.) Graphite spiral.
(iii.) Granular resistance furnaces.
(iv.) Contact resistance furnaces.

The negative temperature coefficients of resistance of carbon and graphite are small and, with these furnaces, no external resistance is necessary to secure stability.

(i.) *Carbon Tube Furnaces.*—The carbon tube furnace is the easiest type of electric furnace to assemble, and is satisfactory for use in small sizes for certain classes of work. The tubes require to be water-cooled at the ends, and in large sizes of furnace, where the amount of heat dissipated at the ends is great, these water jackets are frequently a source of trouble. For mounting tubes up to 2 inches in diameter it is sufficient to make the contacts at the ends of the tubes by means of metal clamps, which may be cast with a fusible alloy in an extemporised sheet-iron or sand mould using a carbon tube as a core. Type metal gives satisfactory results. A copper tube, bent to the form of a spiral, is embedded in the casting. By passing water through this tube the cooling of the electrodes is effected; the tube also serves to carry the current to the furnace.

For larger sizes of furnaces it is convenient to use brass or gun-metal castings for electrodes. A good contact between the carbon and the brass electrodes may be secured by depositing copper on to the carbon either by electro-plating or by a metal spray process and then tinning the surface. There is frequently considerable difficulty in obtaining satisfactory hollow castings for water-cooled electrodes. Satisfactory electrodes, up to any size, may conveniently be made in the laboratory in the following way. A brass annular trough is cast or may be machined out of a solid cylindrical casting if desired. Suitable dimensions of a trough for a 5-inch diameter furnace would be: internal diameter 5 inches, external diameter $7\frac{3}{4}$ inches, thickness of wall of trough $\frac{3}{16}$ inch (leaving an annular space 1 inch wide), depth of trough about 4 inches. A spiral is then made from $\frac{1}{2}$-inch copper or steel tubing of suitable dimensions to fit exactly into the trough. Two turns of tubing in the spiral are sufficient. The spiral is held in position while a fusible alloy is poured into the trough (an alloy of 97 per cent of zinc and 3 per cent of copper has been found suitable). While the metal is still molten two or more brass bolts are inserted head downwards in the trough, leaving an inch of thread exposed. In this way thoroughly satisfactory electrodes may be constructed. Water connections are made with the ends of the spiral tubes, which are allowed to protrude a few inches out of the trough, and flexible cables are attached to the bolts.

Care must be taken to allow for the expansion and contraction of the carbon tubes when in use. At high temperatures carbon becomes weak and breaks on cooling if any strain is set up in the tube. For small tubes a flexible lead on one of the electrodes, with freedom for the tube to slide in a bearing at one end, is sufficient to give the necessary freedom of movement to prevent fracture on cooling, but for larger sizes, 3-inch diameter and upwards, when the electrodes begin to get heavy, rather more elaborate arrangements are necessary. The best results have been obtained by fixing one electrode rigidly and mounting the other on a small trolley running on lines set parallel to the axis of the tube.

It is difficult to obtain large carbon tubes (3 inches or larger in diameter) free from defects; these give rise to local heating and the subsequent graphitisation of the carbon

[1] Harker, *Roy. Soc. Proc.* lxxvi.

in those places, resulting in shrinkage cracks, due to decrease in porosity. For this reason and also on account of the low resistance of large-size tubes (a 4-inch diameter tube has a resistance of perhaps 1/200 ohm) and, consequently, the unwieldy current required, this type of furnace is not suitable for use in large sizes.

It is necessary to adopt precautions to prevent the carbon from burning when hot and, for this purpose, it has been found useful to embed the tube in vegetable black, a finely divided form of carbon obtainable cheaply in large quantities. This material is an excellent thermal insulator and effectively prevents the oxidation of the heating unit. Vegetable black must be handled with care, since, when dry, it is spontaneously inflammable in air at ordinary temperatures. As received, the material contains absorbed moisture and may be stored safely without special precautions, but, after it has been in use in a furnace, it should not be allowed free access to the air for any length of time. It is usual, when a carbon tube is newly mounted, to run it for half an hour at a temperature considerably above that at which it is normally to be used; this serves to drive off volatile constituents (silica, etc.), which would otherwise come off later and contaminate the contents of the furnace.

Various devices have been adopted by different workers to increase the electrical resistance of carbon tube furnaces, such as suitably disposed saw-cuts. While fulfilling this purpose to some extent, the mechanical strength of the furnace is seriously impaired and the advantage of the device is doubtful.

A preparation of graphite, bonded with suitable clay mixtures, has recently been developed for the construction of heating units. This material, which can be moulded to any shape, has a comparatively high specific resistance and a reasonably small temperature coefficient. It does not oxidise readily below 1250° C., and can be used up to 1400° C. without serious oxidation, the bonding material forming a protective glaze. It is hoped, by modifying the bond, to extend the service of this resistor to still higher temperatures.

From these mixtures convenient tube furnaces can be made. It is also possible to construct crucibles for metal-melting to serve the purposes of both the heating element and of the container of the metal. These, when suitably mounted, afford a convenient and rapid method of making experimental meltings.

(ii.) *Graphite Spiral Furnace.*—The use of a graphite spiral as a heating element offers some advantages. The spiral can be cut without much difficulty from a graphite tube, the pitch and thickness being selected to give a resistance suitable for the voltage available. It is useful to shape the tube on the lathe before cutting the spiral, reducing the thickness of the walls at the ends of the tube. The increase in resistance at the ends helps to balance the heat lost there, and a more uniform temperature is produced in the furnace. Three inches of the tube should be left at either end when the spiral is cut, and these ends can be mounted as described above, in the case of the carbon tubes, except that, in this case, no precautions are necessary to allow for the expansion and contraction of the spiral on heating and cooling, since it is sufficiently flexible to take up the change in volume. In assembling for the first run the spiral should be wrapped in paper and then packed in vegetable black. It is found that, when the paper burns off, the vegetable black does not fall in between the grooves of the spiral.

The resistance of these furnaces is comparatively high, of the order of 1/2 ohm (small sizes, 2 inches, may have a resistance up to an ohm or more).

The spiral gives good service if reducing conditions are maintained, but it is very fragile and requires to be handled with care. When broken, it may be repaired by passing a current through the furnace, when local heating will occur at the fracture. The point of fracture is then touched with a mixture of powdered graphite and resin on the end of a rod. The resin melts, runs into the crack and, on further heating, graphitises, forming a sound joint.[1]

(iii.) *Granular Resistance Furnace.*—The granular resistance furnace is a convenient type of furnace where temperatures not much exceeding 1800° C. are required.

The furnace consists essentially of two refractory tubes which are mounted one inside the other, the annular space between them being filled with granular graphite or carbon. *Fig.* 3 shows a diagrammatical section through such a furnace. Owing to the necessity of keeping the ends of the furnace cool, it is difficult to maintain an even temperature distribution. By constructing the furnace as shown in the diagram an even temperature may be obtained over a length of about 3 inches in a tube 12 inches long. The graphite powder employed should be carefully graded to secure uniformity in the size of particles. A size commonly adopted will pass a 16-mesh sieve and is held by a 20-mesh, although finer grades are sometimes used. A granular material may be obtained under the name of Kryptol. This is supplied in various grades having a high or low specific resistance as required. Kryptol consists of carefully graded powdered graphite mixed, in varying quantities, with a material (generally a form of carbon) having a high specific resistance.

A furnace has been described in which

[1] Tarrant, *Faraday Soc. Trans.*, 1920.

granular chromium has been used as a resistor.[1]

Furnaces of this type can readily be constructed to any size required, the limits being

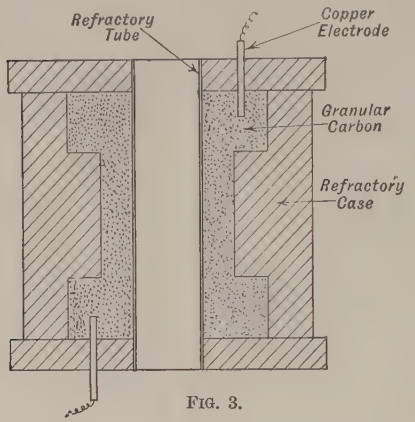

FIG. 3.

set by the size of the refractory liner tube available; powdered graphite or carbon is cheap and can be introduced into the furnace without dismantling; the resistance of the furnace is high, thereby avoiding the inconvenience of excessively high currents, heavy cables, and water-cooled electrodes. On the other hand, the necessity of using a liner tube seriously curtails the utility of the furnace for many experimental purposes; the temperature must be raised carefully to avoid cracking the tube, and, at high temperatures, there is a danger of the tube softening if local heating occurs.

For work up to 1800° C., tubes made from mixtures of clay and alumina are serviceable. Above that temperature magnesia tubes may be used. Pure magnesia tubes and crucibles are apparently not in sufficient demand to encourage manufacturers to produce them commercially in this country; they may, however, be made in the laboratory without great difficulty, not only in magnesia but in pure alumina, zirconia, etc. The pure oxide is melted in a suitably designed arc furnace (see § (5)), finely ground, mixed with a small quantity of powdered gum-tragacanth and moistened with water. The damp powder is then pressed into a metal mould consisting of an outer tube and a solid removable core. When the mould is filled the outer tube may be removed, leaving the pressed magnesia tube on the core. A sheet of paper is then wrapped round the magnesia tube, and, holding the tube loosely in the hand, the core can be withdrawn. If the oxide has been brought to the right consistency before moulding, this operation is simple to carry out and gives satisfactory results. By this means electric furnace parts, crucibles, etc., may be made from pure CaO, MgO, ZrO_2, Al_2O_3, etc., in the laboratory. The tubes, when moulded, should be dried and fired, standing vertically, to 2000° C., in an electric furnace either of the type described above fitted with a magnesia liner or in a furnace of the ring type (see § (4)). The required temperature can also be obtained in an oxy-gas furnace.

(iv.) *Contact Resistance Furnace.*—This type of resistance furnace, which has a wide range of application, utilises the resistance at the contact of a series of graphite rings arranged to form a cylinder.[2]

For this purpose rings, having a radial thickness of about a $\frac{1}{2}$ inch, are cut from a graphite rod or tube, their surfaces of contact making an angle of 60° with the axis of the tube. (This arrangement increases the stability of the furnace.) The cylinder is preferably mounted in a substantial steel casing, to protect the rings from shock. The construction of the water-jackets is similar to the other types described above. It is found that with this furnace it is not necessary to tin the ends of the graphite at the contact with the brass electrodes; a taper fit gives satisfactory results.

This furnace has many advantages. It can be constructed in large sizes without the necessity of using a heavy current, since the resistance of the furnace may be increased as desired by increasing the number of rings per unit length of furnace tube. The effect of heat losses at the ends of the furnace may be reduced by increasing the resistance at the top and the bottom in this manner. It is not necessary to use a liner tube, as in the case of the granular resistance furnace, and, in consequence, extreme temperatures (over 2500° C.) can be obtained when desired.

However, a liner can be introduced if an oxidising atmosphere is required. An even distribution of temperature can be maintained by adjusting the pressure on the rings by means of suitably disposed springs attached to the upper electrode. The furnace eventually breaks down owing to the gradual oxidation of the graphite. This usually occurs locally, at the top or bottom of the furnace, and it is only necessary to substitute new rings in the place of those badly oxidised.

The power required to run these furnaces varies considerably with the thermal insulation employed. Roughly speaking, using about 6 inches of vegetable black and 3 inches of light magnesia packing, a furnace 3 inches bore and 15 inches long will take about 10 kilo-volt-amperes, running at 1600° C. A

[1] Dony-Hernault, *Comptes Rend.*, 1913, clvi.

[2] Rosenhain and Coad-Pryor, "A High Temperature Electric Resistance Furnace," *Faraday Soc. Trans.* xiv. Part 3.

larger furnace, 7-inch bore, similarly mounted, would take 20 kilo-volt-amperes to reach the same temperature. The temperature in graphite resistance furnaces may be raised as rapidly as desired, provided that they are not fitted with refractory liner tubes. 2000° C. may readily be obtained in 5 minutes without damage to the furnace.

It is, of course, necessary to exclude oxygen from the graphite when the furnace is running at temperatures over 600° C. The usual practice is to pass nitrogen slowly through the furnace when in operation. (The nitrogen consumption is small, 1 c. ft. will last for about 2 hours.)

Northrup describes a graphite resistance furnace built up on the cascade principle. A carbon resistance furnace, which forms the outer heater, is run at 1600° C. The atmosphere inside this furnace becomes saturated with carbon vapour, with the result that the inner heater (a graphite tube about 8 cm. long, 1·5 cm. bore, and 1 mm. thick, screwed into graphite blocks) may be raised to an exceedingly high temperature, over 3000° C., without disintegration. Tungsten can be melted in this furnace without difficulty.[1]

When working with any furnace which contains carbon or graphite it is important that care should be taken to secure thoroughly adequate ventilation in the furnace-room. In small rooms arrangements should be made to conduct the waste gases from the furnace out of the room, and on no account should gases be permitted to leak through the furnace casing into the room; a proper exit for the gases should always be provided.

§ (4) Induction Furnace.—A furnace which promises to become a valuable addition to the equipment of research laboratories has been developed by Northrup and has now been placed on the market.

The furnace consists essentially of a primary coil of wire through which a current of high frequency is passed (1200 or more cycles per second). Any conductor which is placed inside this inductor coil becomes heated by the heavy secondary currents which are induced in it. Thus, a charge of metal in a clay crucible or a charge of non-conducting material in a graphite or metal crucible may be heated rapidly and efficiently, since the energy is converted into heat at the point where the heat is required.

The furnace also has great possibilities for firing to very high temperatures crucibles and other articles made from refractory materials having large negative temperature coefficients. These could be heated by enclosing them in a graphite cylinder until they reached a temperature at which they became sufficiently good conductors to carry large induced currents. The graphite cylinder could then be removed. This furnace offers obvious advantages for work *in vacuo* (pure iron has been successfully melted *in vacuo* in magnesia crucibles), and also has the merit that it cannot easily be burnt out.

The installation is, unfortunately, expensive at the present time, but it is possible that, when powerful high-frequency alternators are obtainable at a reasonable price, this furnace will prove to have a very wide range of utility.[2]

§ (5) Arc Furnaces.—The arc furnace is the earliest and most primitive type of electric furnace used for experimental work. Generally speaking, it is only used where the maximum temperature obtainable is required and where overheating and contamination of the charge are not objectionable.

The temperature in the arc crater is probably about 3500° C.—although some investigators consider that this estimate is too low.

Since, with an arc furnace, intense local heating is always obtained, refractories of the highest grade only have to be employed in its construction. Those parts of the furnace exposed to the maximum temperature should be made of magnesia where possible, or, at any rate, faced with magnesia, since this oxide has a high melting-point and is the only oxide which does not form a carbide or sub-oxide at high temperatures.

In its simplest form the furnace consists of two carbon or graphite electrodes mounted horizontally in a magnesia or lime block which is slotted to hold the electrodes and hollowed out in the centre to take the charge to be melted or a crucible containing the charge. *Fig.* 4 shows a diagrammatic section.

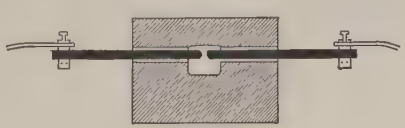

Fig. 4.

Some such simple arrangement can easily be extemporised in the laboratory.

Convenient and more elaborate arc furnaces can be obtained in a variety of types. The electrodes may be mounted horizontally or inclined at an angle of 45° to the horizontal. In one form of arc furnace, sometimes useful, the electrodes are vertical, the lower being in the form of a graphite cup and the upper a rod, vertically above it, which can be raised or lowered as desired by means of a screw. Arc furnaces have also been designed and placed on the market for the distillation of

[1] Northrup, *Metallurgical and Chemical Engineering*, 1914, xii. No. 4. See also "Furnaces, Electric," § (8).

[2] Northrup, "Principles of Inductive Heating with High-frequency Currents," *Am. Electrochem. Soc. Trans.*, 1919, xxxv.

materials having high boiling-points, such as silica, and for the fusion, by a continuous process, of considerable quantities of refractory oxides.

The carbon electrodes, which should be made from carbon giving as small an ash as possible, are usually held in copper or brass clamps to which flexible cables are attached. The clamps are mounted on a simple mechanical device for adjusting the length of the arc and withdrawing the carbons from the furnace when desired. If the correct size of electrodes has been selected it is not necessary to water-cool the clamps. Working at a voltage of between 50 and 60, the carbons should be approximately :

2·5 cm.	diameter	for an	arc of	100 amps.
3·0 „	„	„	„	150 „
4·0 „	„	„	„	250 „
8·0 „	„	„	„	500 „

A useful type of arc furnace for general experimental purposes has been designed by Borchers. The carbons can readily be adjusted to work horizontally, vertically (the lower being in the form of a cup), or inclined symmetrically at right angles to each other. The furnace may also be used as a resistance furnace. For melting purposes direct or alternating currents may be used.

When running an arc it is desirable to have an ammeter and a voltmeter in operation, by means of which the course of the experiment may be controlled and the correct adjustment of the electrodes maintained. If the arc is allowed to go out it is often difficult to strike it again in the middle of a run. It will generally be found necessary to withdraw the electrodes as the melt proceeds, since the atmosphere in the furnace becomes charged with metallic vapours and the resistance falls.

(i.) *Preparation of Fused Refractory Oxides.*—It is sometimes required to prepare fused magnesia, lime, zirconia, etc., in the laboratory. For this purpose it has been found convenient to adopt the following procedure in preference to the usual continuous feed arc furnaces.

Two large graphite electrodes—say 6 inches diameter—are placed about 2 feet apart in a trough built in fire-brick. These electrodes are connected by means of a thin carbon tube or rod, half an inch diameter or less. The trough, which is about 1 foot deep, is then filled with the powder to be melted and a heavy current passed through the circuit; 50 volts between the electrodes is sufficient. The carbon rod becomes hot, together with the powder immediately surrounding it. In a few seconds the powder becomes a sufficiently good conductor to carry a heavy current (since all oxides have a high negative temperature coefficient of resistance). The carbon rod soon burns away, leaving the molten oxide carrying the current. Since the system is unstable it is necessary to feed on more of the powder to cool the charge and to prevent it from burning out the trough. By this means a large quantity of highly refractory material can be quickly melted without difficulty.

When manipulating an arc furnace precautions should be taken to protect the skin and, more particularly, the eyes of the operator from the glare of the arc. Even a comparatively small arc—1 kilo-volt-ampere—can cause a severe burn on the skin of the face and seriously damage the eyes.

§ (6) Vacuum Furnace.—Temperatures up to 1000° C. may conveniently be attained, *in vacuo*, in a silica tube. Silica tubes, with one end sealed, may be obtained in any dimensions. The object to be heated is placed in the tube near the sealed end and the tube placed in any furnace of a suitable size. The tube must be of sufficient length to secure that the open end projects far enough out of the furnace to remain cool. This end may then be plugged with a tightly fitting rubber bung fitted with a glass tube leading to the vacuum pump. If necessary the joints may be painted with sealing-wax varnish (a solution of sealing-wax in alcohol).

For vacuum work at higher temperatures more elaborate equipment is necessary. It is possible to use hard porcelain tubes, as above, up to 1450° C., but they are liable to crack and can seldom be used more than once. If much work is to be carried out *in vacuo*, it is preferable to use a furnace specially designed for it. The type of furnace most widely used is the Arsem vacuum furnace.[1]

A graphite spiral forms the heating element, the ends of which are mounted in water-jackets in the usual way. The tubes carrying the water also serve to carry the current for the furnace. The spiral and water-jackets are enclosed in an air-tight gun-metal casing, fitted with a small mica window for observation purposes. When running, the whole furnace is immersed in water to prevent the gun-metal case from becoming heated.

To avoid introducing material which, when heated, will give off volatile constituents, the graphite spiral should not be packed with insulating material which, in the absence of convection currents in the furnace, is unnecessary. To cut down the radiation, the spiral is enclosed in a thin double-walled cylinder of graphite, the space between the walls of the cylinder, about $\frac{1}{4}$ inch, being filled with powdered graphite. A space of about $\frac{3}{4}$ inch should be left between the cylinder and the spiral.

The furnace can be used conveniently at temperatures up to 2500° C. Above that

[1] *Am. Electrochem. Soc.*, 1906, ix.

temperature the volatility of the graphite becomes serious and the spiral burns out quickly. The life of the spiral, *in vacuo*, is about 1 hour at 3000° C., 10 hours at 2500° C. It will last for many days at temperatures below 2000° C.

It is found that, with this type of furnace, the temperature may be calibrated in terms of the energy consumed, a fact which is sometimes convenient for high-temperature work when the presence of fumes makes the manipulation of an optical pyrometer difficult.

§ (7) High-pressure Furnace.—A convenient furnace for work at high pressure (up to 2000 atmospheres) has been designed by Hutton and Petavel.[1]

It is of the arc furnace type, mounted in a steel shell lined with cast iron. The electrodes enter through specially designed stuffing-boxes. The furnace could be modified, if desired, for use as a resistance furnace.

The vacuum and high-pressure furnaces mentioned above are designed to run, if necessary, at temperatures over 2000° C. If lower temperatures only are required, it is a comparatively simple matter to convert a platinum-wound resistance furnace into a vacuum furnace by mounting it in a steel shell which can be evacuated. When used as a vacuum furnace, the thermal insulating material should be removed and one or more clay or porcelain cylinders placed round the platinum winding to cut down radiation losses.

§ (8) Cathode Ray Furnace.—For special purposes the heat developed by the bombardment of a body by cathode rays has been utilised for melting purposes. Small quantities of platinum, boron, tantalum, etc., have been melted in a silica bulb, using a 20-cm. spark. Massive aluminium cathodes and anodes were used.[2]

§ (9) Gas Furnaces.—Although, in many cases, electric heating is to be preferred for laboratory work, there are some purposes for which gas-firing is more convenient. For metal-melting on an experimental scale, where extreme accuracy of temperature control is not desired, and for the heat treatment of comparatively large quantities of material involving a furnace capacity of a cubic foot or so, the use of electric heating becomes expensive. In cases where temperatures between 1000° C. and 1500° C. are required, electric resistance furnaces wound with base metal wire are not sufficiently durable for prolonged use, and platinum-wound furnaces are too expensive in large sizes. Again, the use of carbon as a resistance involves the maintenance of a reducing atmosphere which is inconvenient.

[1] Hutton, *Roy. Soc. Phil. Trans.*, Series A, 1908, ccvii. See also Fischer and Plotze, *Zeit. für anorg. Chem.*, 1912, lxxv.

[2] *Berichte der Deutschen Chemischen Gesellschaft*, 1913, vol. xlv.

There are many types of gas furnaces available, and catalogues of small melting-furnaces and muffles for heat treatments of all kinds are published by a number of firms. From these catalogues detailed descriptions of the furnaces can be obtained, and instructions for use and hints for efficient running and upkeep are supplied with the furnaces by the makers.

The flame temperature of a Bunsen burner is probably very near to 1800° C. (However, some authorities have estimated it to be as high as 1870° C.) Coal gas fed with oxygen will give a flame temperature of 2200° C., while the temperature of the oxyhydrogen flame is 2400° C.

Generally speaking, small natural draught furnaces will give temperatures up to 950° C. without difficulty. These do not require a great chimney draught—a few feet of stove-pipe being sufficient. Of the small furnaces, the Cunynghame muffle furnace is probably the most efficient. This furnace is well "lagged" with magnesia or kieselguhr, which is enclosed in a uralite case. A Bunsen burner, or a petroleum lamp, is used to heat the furnace; no chimney is required.

In some types the air is pre-heated by passing through flues running round the combustion chamber; in these furnaces 1350° C. can be obtained when in good repair.

It is advisable when installing a gas furnace to fit gas-pipes leading to the furnace rather larger than the standard size recommended in the makers' catalogues. Better results are obtained with a high pressure through a small jet than with a low pressure and a large jet

The furnaces as supplied are generally fitted with fire-clay muffles. Increased efficiency and longer life can be obtained by the use of carborundum muffles, which have a high thermal endurance and a high thermal conductivity and are well worth the extra initial cost. Carborundum furnace parts must not, however, be used in places where they may come in contact with metallic oxides at temperatures over 950° C.

A small natural draught non-recuperative furnace will give a temperature of about 900° C. in a muffle $4 \times 3 \times 7$ inches with a gas consumption of about 60 c. ft. per hour. A muffle $12 \times 6 \times 14$ inches would require about 200 c. ft. per hour to reach 900° C.

A natural draught laboratory furnace of the recuperative type was designed by Seger for testing refractory materials. *Fig.* 5 shows a diagram illustrating the construction of the furnace. The air, entering at A, is pre-heated by the exhaust gases before it reaches the gas inlet at B. The flame passes upwards to the top of the furnace and then down the centre as indicated by the arrows. With proper adjustment of gas and damper,

a temperature exceeding 1500° C. may be attained.

A larger recuperative furnace working on natural draught has been designed at the National Physical Laboratory for the firing and

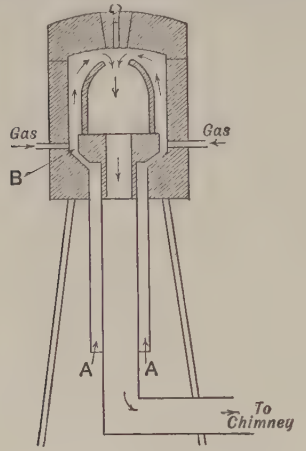

FIG. 5.

testing of experimental refractory materials and for experimental glass-melting.[1]

In this furnace the air enters through horizontal carborundum tubes which are heated by the exhaust gases. *Fig.* 6 is a plan of the furnace showing the recuperator.

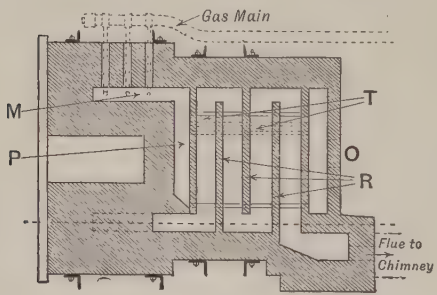

FIG. 6.

O, Air inlet; T, carborundum tubes; R, clay baffles; P, flue leading to combustion chamber; M, combustion chamber.

A temperature of 1650° C. can be reached in a working space of $36 \times 18 \times 15$ inches with a gas consumption of about 650 c. ft. per hour, showing a high efficiency. The furnace is silent in operation and can be left at night without attention.

A furnace has also been designed to work on the regenerative principle. This furnace has two regenerators, and the exhaust gases and the incoming air are passed through each alternately in the usual way. Temperatures up to 1700° C. may be obtained in this furnace, but it has certain drawbacks: the air and gas are introduced under pressure and the valves controlling the regenerators have to be operated every half-hour. Consequently the furnace cannot be allowed to run unattended and in this respect is inferior to the recuperator furnace described above.

To obtain the maximum temperatures, it is necessary to ensure efficient mixing of the gas and air to produce a short flame.

§ (10) SURFACE COMBUSTION FURNACES.—The surface combustion furnace offers many advantages for the production of very high temperatures if certain practical difficulties relating to it could be overcome.

In this system of firing, the gas and air are fed into a mixing chamber in the proportions required to give complete combustion. (In practice a slight excess of air is generally used.) The explosive mixture is then forced through a porous refractory material and burns quietly at the surface of the refractory, which reaches a high temperature to a depth of about a $\frac{1}{4}$ inch. The success of the furnace depends on the maintenance of the correct mixture in the mixing chamber and on the careful regulation of the velocity of the gases through the porous refractory. The refractory surface should be composed of a material having a high sintering point and a low thermal conductivity—such as fused zirconia.

§ (11) HIGH-PRESSURE BURNERS.—Temperatures up to 1650° C. or 1700° C. can be obtained by the use of burners designed either to work with gas at a few inches pressure and air at high pressures (up to 80 or 100 lbs. per sq. inch) or with both gas and air under a low pressure of a few pounds. Temperatures up to 1700° C. can be reached rapidly without pre-heating the air. With pre-heated air 1800° C. or more can be attained. These burners are very noisy when working, they give an intense, cutting flame, and it is very difficult to obtain a uniform temperature in the furnace.

There are no fire-clays which will withstand the cutting flame of these injector burners. The life of the furnace may be prolonged somewhat by coating the walls and floor with a wash composed of carborundum with 5 per cent of refractory clay. This must be renewed from time to time, since the carborundum oxidises slowly at temperatures above 1500° C. To give a long life, the furnace should be lined with a half-inch layer of ground fused alumina mixed with 10 per cent of china clay.

Where very high temperatures are required compressed oxygen may be used instead of air. Temperatures of over 2000° C. may then be reached. The furnace must then be lined with lime, magnesia, or zirconia, to withstand the cut of the flame.

[1] Rosenhain and Coad-Pryor, "A New Type of Recuperative Furnace," *Ceramic Society Trans.* xviii. Part 2.

Where possible, governors should be fitted to the laboratory gas mains. This is particularly desirable if the furnaces are required to be left running at night, since many gas companies reduce the gas pressure during the night. Governors, for use with furnaces requiring both gas and air under pressure, can also be obtained to adjust, automatically, the relative pressures of gas and air to ensure a perfect mixture.

§ (12) Miscellaneous.—Where a supply of gas is not available, furnaces operated by paraffin can be used. The paraffin is fed, under pressure, into a burner which vaporises the oil, producing a hot flame. Such a furnace will heat a 10-lb. crucible to 1450° C. in about one and a half hours with a consumption of about half a gallon of paraffin per hour.

Experimental furnaces fired with coal and coke are in use, principally for assaying and melting purposes, where gas is not available.

A convenient furnace for certain classes of test work—particularly for the determination of the softening-point of refractories—is the well-known Deville furnace, which consists of a refractory cylindrical case, usually about 12 inches in diameter and 18 inches high, with an iron grating at the bottom. The specimens to be heated are placed in a refractory tube in the centre of the furnace and the space between the tube and the outer casing packed with coke. An air-blast is introduced through the grating. The coke, which is first heated by gas, rapidly becomes incandescent and very high temperatures may be obtained in a few minutes. The maximum temperature is usually about 3 inches from the bottom. If suitable coke has been selected, platinum can be melted in this furnace.

For details of insulating materials, see article on "Heat, Conduction of," § (3), Vol. I.

E. A. C.-P.

Fusible Alloys. See "Alloys, Some Special," § (7).

G

γ-iron. See "Iron-carbon Alloys," § (3).

Galvanising: preventing corrosion in iron and steel by applying a protective coating of zinc. See "Metals, Defects and Failure of," § (6).

Gas Furnaces. See "Furnaces for Laboratory Use," § (9).

Gaseous Reagents for etching metals and alloys. See "Metals, Microscopic Examination of," § (2) (iii.).

Geodetic Base, use of Invar in measurement of. See "Invar and Elinvar," § (10); see also "Surveying Tapes and Wires," Vol. III.

Gibbs, Willard, phase rule of. See "Alloys, Constitution of," § (1); see also "Phase Rule," Vol. I.

Girders, made from mild carbon steel. Analysis; mechanical tests. See "Steels, Special," § (46), Table 9.

Glass-melting Furnaces. See "Furnaces, Electric," § (9).

Gradient Furnaces. See "Furnaces for Laboratory Use," § (2); also "Metals, Thermal Study of," § (2).

Granular Resistance Furnace. See "Furnaces for Laboratory Use," § (3) (*c*).

Graphite, furnace for making. See "Furnaces, Electric," § (5) (iii.).

Graphite Constitution and Properties. See "Refractories," §§ (42), (43).

Graphite Resistance Furnace. See "Furnaces for Laboratory Use," § (3).

Graphite Spiral Furnace. See "Furnaces for Laboratory Use," § (3) (*b*).

"Grog" as used in Refractories. See "Refractories," § (10).

H

Hardening, in carbon steels, consists in heating above the critical range (Ac_1) followed by quenching in water or oil. In other steels (such as high-speed tool steels) higher temperatures and slower rates of cooling are used. See "Steels, Special," § (43).

In connection with plastic deformation of metals. See "Metals, The Relations of Strain and Structure," § (1).

Of steel. See "Iron-carbon Alloys," §§ (11), (12).

Of steel, theories of. See *ibid.* § (12).

Hardenite, theory of its presence in steel. See "Iron-carbon Alloys," § (12).

Hardness of Special Steels, Bimell and Shore methods of testing. See "Steels, Special," § (2).

HEAT TREATMENT: the method of securing certain desired conditions in a metal or alloy by a series of changes of temperature applied at definite rates. See "Metals, Defects and Failure of," § (5).

Of steel. See "Iron-carbon Alloys," § (10).

HEATING CURVE in construction of equilibrium diagram. See "Alloys, Constitution of," § (2) (iii.).

HÉROULT FURNACE: a typical furnace for the reduction of iron ore. Designed by Héroult in 1906. See "Furnaces, Electric," § (4) (ii.).

HIGH PERMEABILITY STEELS. See "Steels, Special," § (51).

HIGH-PRESSURE BURNERS. See "Furnaces for Laboratory Use," § (11).

HIGH-PRESSURE FURNACE: a convenient furnace (of the arc furnace type) for work at high pressure, designed by Hutton and Petavel. See "Furnaces for Laboratory Use," § (7).

HIGH-SPEED STEEL, used in cutting-tools (machine) to withstand heat due to heavy or fast cutting. See "Steels, Special," § (47) (ii.), Table 18.

HOT ROLLING: passing heated metal through a pair of rolls. See "Metals, Thermal and Mechanical Treatment of," § (6).

HOT WORKING: producing changes of shape in a metal by the application of stress while the metal is hot. See "Metals, Defects and Failure of," § (3).

HYDROGEN in steel. See "Steels, Special," § (12).

— I —

ILLUMINATION, NORMAL: the method of illuminating a specimen under microscopic examination so that the light falls upon the surface of the specimen in a direction at right angles to that surface. See "Metals, Microscopic Examination of," § (6).

IMPURITIES in steel. See "Iron-carbon Alloys," § (14).

INDIRECT ARC FURNACE: an arc furnace in which the arc is struck between the electrodes and the charge heated by radiation. See also "Furnaces, Electric," § (2) (ii.).

INDUCTION FURNACE. See "Furnaces for Laboratory Use," § (4); see also "Furnaces, Electric," §§ (4) (vi.), (8).

INGOTS, structural defects in. See "Metals, Defects and Failure of," § (2).
Mechanical defects. See *ibid.* § (2).

INTERNAL STRESS: a cause of spontaneous cracking in hardened steel. See "Iron-carbon Alloys," § (11).

INVAR AND ELINVAR

I. PROPERTIES OF THE MATERIAL

§ (1) DEFINITION.—*Invar* (short for *invar*iable) is an alloy of iron and nickel which is practically destitute of thermal expansibility.

Elinvar (short for *el*asticity *invar*iable) is an alloy of iron and nickel, with a considerable admixture of other metals or metalloids, possessing an invariable modulus of elasticity (Young's modulus).

The characteristic qualities of invar and elinvar are due to an anomaly which affects all the properties of alloys of iron and nickel. The essential features of this anomaly are described below.

§ (2) REVERSIBLE ALLOYS AND IRREVERSIBLE ALLOYS.—The first of the peculiar properties of alloys of iron and nickel was discovered in 1888 by Dr. John Hopkinson. An alloy of iron with 24 per cent of nickel, if allowed to cool from the temperature of the forge to that of the air, is non-magnetic and relatively soft. On the other hand, if its temperature has been considerably reduced and then brought back to its initial value, the alloy is magnetic and hard, and its volume is found to be increased by about 2 per cent. To restore the properties that it possessed before cooling it must again be raised to a red heat. Guillaume showed (1896) that the transformations of the iron and nickel alloys may be represented as occurring along two curves which, starting together for iron, separate from one another as they proceed. Of these curves AB (*Fig.* 1) represents the

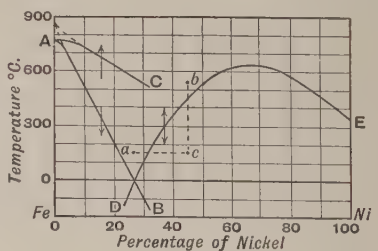

FIG. 1.

occurrence of magnetisation on cooling, and AC the disappearance of magnetisation on heating. All the alloys comprised within the region of these two curves undergo irreversible

transformations, and may be called, for brevity, *irreversible alloys*.

For higher percentages of nickel, the alloys undergo reversible transformations: the curve DE shows the temperatures at which these alloys commence to be magnetic when the temperature is falling, and cease to be magnetic when the temperature is rising (Guillaume, 1896; Osmond, 1897). Dumas found (1897) that the curves of the two kinds cut one another, and Chevenard proved (1913) that the curve AB tends towards absolute zero for the alloy containing two atomic parts of iron to one of nickel.

All the properties of the nickel-steel alloys are dependent upon the transformations indicated by the occurrence and progressive increase of magnetisation, or its decrease and disappearance. In what follows we will confine our attention to the reversible alloys.

§ (3) Corresponding States.—An alloy of which the composition and the temperature are represented by the point *a* is non-magnetic, so is an alloy represented by the point *b*. On the other hand, the point *c* represents a magnetic alloy. We may, however, reach the point *c* by starting from *a*, if the temperature is maintained constant and the composition of the alloy altered in a continuous manner. Conversely, we may pass from *b* to *c* by retaining the same composition and changing the temperature. For points not too remote from the curve DE, the magnetisation increases constantly in both these cases. The alloys situated on the straight line *ac* will pass through all those susceptibilities which are met with in one and the same alloy along the straight line *bc*. As regards susceptibility, each point of the straight line *bc* corresponds to a single point of the straight line *ac*, and the series of points will be arranged in the same order. If we say that the alloys having the same susceptibility on these two fragments of straight lines are *in corresponding states*, we shall be able to conceive a law of corresponding states which may be formulated in the following terms: The properties of the continuous series of alloys with increasing percentage of nickel, considered at the same temperature, are reproduced in the properties of one and the same alloy, considered at continually decreasing temperatures.

It is true that an exhaustive investigation of these alloys shows that the above law, as applied to all their properties, is not rigorously exact. The law is, however, sufficiently close to the truth to enable us, after studying the properties along the line *ac*, to predict what is likely to occur along the line *bc*. We shall find examples of this further on.

§ (4) Nature of the Alloys.—It should be clearly understood that the alloys whose properties are about to be described are not composed solely of iron and nickel in the pure state, but contain also small quantities of manganese, carbon, and silicon, which are inevitable in metallurgical products, or indispensable for the working up of bars. As will be seen further on, a detailed examination has made it possible to establish, for each percentage content of nickel, the changes which the properties of the alloy undergo corresponding to the quantities of manganese and carbon contained in it, and also to deduce typical conditions. The following data refer to alloys containing 0·4 Mn and 0·1 C per cent. Alloys rolled when hot and cooled in the air will be called "in the natural state."

§ (5) Expansibility.—This is usually expressed by an equation of the form

$$l = l_0(1 + a\theta + \beta\theta^2),$$

where a and β are coefficients which are constant throughout a wide range of temperature. The expansibilities of the nickel-steel alloys can only be represented by an equation of this form within rather narrow limits of temperature. Throughout the range 0-40° C. β denotes a quantity which is sufficiently constant to admit of the equation being applied. For the typical alloys "in the natural state" the values of a and β, in terms of the percentage of nickel, are represented by the

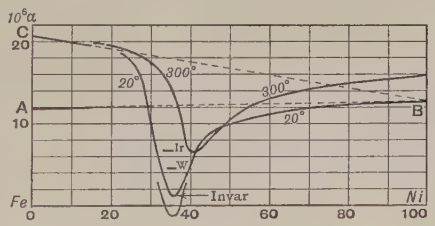

Fig. 2.

curves in *Figs.* 2 and 3. It should be mentioned that these coefficients refer strictly to the temperature of 20° C. only.

In *Fig.* 2 the two straight lines AB and CB indicate the expansibilities which might be

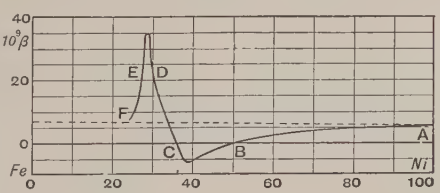

Fig. 3.

predicted from the law of mixtures, if the iron were considered in the two cases as stable when cold and stable when hot respectively

(alpha iron or gamma iron). For the alloys rich in iron the expansibility actually observed is greater than that given by the line AB; as the percentage of nickel increases, the expansibility curve falls below the line AB, while for all the alloys it is below CB. Theoretical considerations show that the latter representation can alone be correct.

Commencing with a high value, at the starting point of the reversible alloys, α diminishes very rapidly, passes through a minimum, then increases and attains the value proper to nickel. The minimum represents invar: Ni = 35·6 per cent, $\alpha = 1{\cdot}19 \times 10^{-6}$.

The values of β exhibit a no less marked singularity; referred to the straight line representative of the law of mixtures, they present an anomaly at first. The values are greater than those given by the normal curve, then they become less. In the region of 36-51 per cent of nickel, the values of β are actually negative, a property which has not been met with, up to the present, in any other series of alloys.

Combining the values of α and β, we see that the curves of true expansibility for temperatures slightly greater than 20° C. deviate from the normal curve in an upward direction for the alloys containing from 25 to 36 per cent of nickel, then from 36 to 51 per cent they deviate downwards, and at 51 per cent pass again above the initial curve.

Owing, however, to the values of β given by the curve in *Fig.* 3 not being sufficiently exact, for most of the alloys, except within a narrow range of temperature, the curves corresponding to the several temperatures can only be drawn with precision after direct determinations. We have shown in *Fig.* 2, as an example, the curve corresponding to 300° C.; this still preserves a trace of the consequences which follow from the values of β at 20° C.

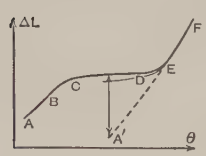

Fig. 4.

The expansion of a bar of a nickel-steel alloy, of any percentage composition whatever, is represented in a general way by a curve, such as ABCDEF (*Fig.* 4), in which all the effects due to the changes of β as indicated by *Fig.* 3 are reproduced. Here we have an example in support of the law of corresponding states.

The curve FA′ indicates the contraction which, in the absence of anomaly, the alloy should undergo on cooling The distance of A′ from the actual curve denotes, for each temperature, the intensity of the anomaly.

The expansibility of nickel-steel alloys of percentage compositions close to that of invar depends upon the processes to which they have been subjected. The effect of reheating, followed by slow cooling, is to raise the central portion of the curve; that of sudden cooling (quenching) is to lower it. Such processes as hammering or working up (rolling, forging, cold drawing) also depress it. This lowering effect may be so considerable as to lead, in the case of invar, to negative values of α. Moderate heating (100 to 200° C., for example) raises the expansibility of alloys that have been quenched, or subjected to the processes of hammering or working up, and even of alloys "in the natural state." By thermal treatment, an alloy of the α negative type may be brought up as close to $\alpha = 0$ as may be desired.

It will be noticed that β passes through its zero value precisely for invar, and accordingly

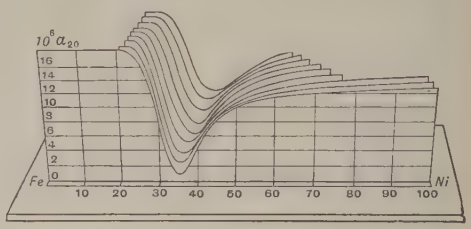

Fig. 5.

the expansibility of this alloy is linear, at least within a moderate range of temperature.

§ (6) Effect of Additional Constituents. —The properties of the ternary alloys can only be represented satisfactorily by means of a Guthrie diagram (*Fig.* 5 illustrates this); all other modes of representation involve some arbitrary assumption. In the diagrams given below, the percentages of nickel are retained as abscissae; but in this case the percentage of iron is the difference between 100 and the sum of the percentages for nickel and the additions. With this reservation, the path of the minimum of expansibility (α_{20}) is represented in *Figs.* 6 and 7 in terms of abscissae and ordinates. The first diagram shows that the abscissa may be displaced either towards the high or towards the low per-

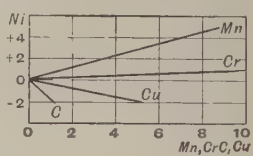

Fig. 6.

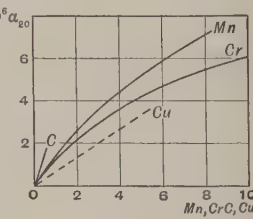

Fig. 7.

centages of nickel; the second, that all additions increase the ordinate of the minimum.

In *Fig.* 8, the curve relative to the typical alloys is reproduced, as well as the curves

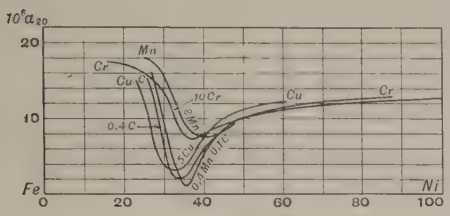

FIG. 8.

referring to the highest percentages of additions that have been realised.

§ (7) ELASTIC PROPERTIES; YOUNG'S MODULUS AND ITS THERMAL VARIATION.—For the whole series of reversible alloys, Young's modulus, denoted by E, is less than the value derived from the composition: its minimum value, which is situated in the region of minimum expansibility, is, for the binary alloys, $1{\cdot}4 \times 10^{12}$ C.G.S. The presence of chromium or manganese increases its value, that of copper or carbon diminishes it.

The coefficient of thermal variation of Young's modulus (thermoelastic coefficient), $\epsilon=(dE/d\theta)$, exhibits with respect to the percentages of nickel an anomaly quite as remarkable as that of the expansibility. The values of this coefficient are represented, for the typical alloys, by the curve A in *Fig.* 9,

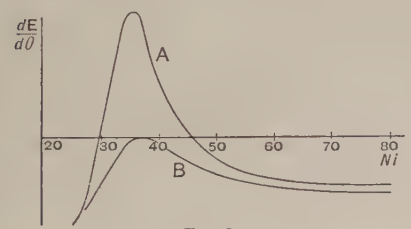

FIG. 9.

and are at first negative, as in all other metals or alloys, but rise as the percentage of nickel increases, pass through zero, continue to rise until a positive maximum is reached, and then fall again, to arrive finally at the value proper to nickel.

The values of the quadratic term in the complete formula have not been determined with precision for all the alloys. By aid of the law of corresponding states we may, however, conclude that the successive values of Young's modulus, for one and the same alloy, throughout a wide range of temperature, are represented by a curve such as A (*Fig.* 10). The maximum and the minimum indicate two zero values of the thermoelastic coefficient, which correspond respectively to the first and the second intersection of the curve A (*Fig.* 9) with the axis. At ordinary temperatures these two alloys possess the property indicated by the name *elinvar*.

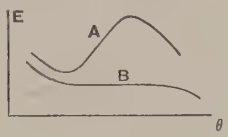

FIG. 10.

It should, however, be noted that the value of E is only zero in virtue of the existence of a maximum or a minimum of Young's modulus, and therefore within an indefinitely small interval of temperature.

The form of the curve A (*Fig.* 9) is in almost complete agreement with that of the curve of expansibility (*Fig.* 2). If it is assumed that the curves will remain similar in the case of the ternary alloys, we may infer that the additions will lower the maximum of the curve A.

Experimental results have verified this view, and it is now known that, by means of suitable additions of metals or metalloids (with an unlimited range of choice), the curve representing the values of E can be made to touch the axis (curve B, *Fig.* 9). If the addition consists of chromium alone, this condition is realised when the quantity added amounts to 12 per cent. The effect of other additions will of course be to deflect the maximum to right or left, as in the case of the expansions.

Applying the law of corresponding states, we see that, for a given alloy, the zero value of E will necessarily come between two negative values. The complete curve for one and the same alloy will therefore have the form represented by the curve B (*Fig.* 10), in which two descending branches, of strongly marked curvature, are connected by a portion which may be made horizontal and which indicates the existence of alloys having an invariable modulus of elasticity, and therefore really elinvar (Guillaume, 1919).

§ (8) INSTABILITY.—When the temperature of a bar of nickel-steel of typical invar is altered from the value θ_1 to the value θ_2, the bar does not immediately assume its definitive length; if $\theta_2 > \theta_1$ the bar, after increasing in length in conformity with its expansion equation, exhibits a small retrograde effect, which may be detected during a period measured by minutes, hours, days, or even weeks, depending on the value of θ_2 and on the state of the bar. If restored to the temperature θ_1, it shortens to the same extent as it increased in length when its temperature was first altered, and then undergoes an elongation, which takes place more slowly than the secular change observed at

θ_2, and may be traced for years at the ordinary temperature.

These actions are subject to laws analogous to those on which the changes in glass depend, which have long been known to physicists from observations of the zero point of mercury thermometers. It appears, moreover, that the total action observed in both of these cases is due to the superposition of two distinct phenomena: a change of a transitory character, and a progressive change.

A bar of typical invar, cooled in air from the temperature of the forge and maintained at 100° C., elongates at that temperature by about 30 μ per metre, and this expansive action may be easily followed during 100 hours. If the bar be then rapidly cooled to 0° C. after its first contraction, it again elongates, in the course of some years, by an amount also close to 30 μ per metre. If it be then heated to an intermediate temperature, the bar shortens; the observed differences between the initial and the definitive value at each temperature may then be adequately represented by an equation of the form

$$\Delta l = -al\theta^2,$$

θ being the temperature reckoned from 0° C.

For bars of typical invar (with 0·1 per cent of carbon), it is seen from what precedes that a is approximately 3×10^{-9}.

This coefficient varies rapidly with the percentage of nickel in the alloy: between 42 and 43 per cent of nickel it vanishes, then assumes a negative value and rises slowly, to become definitively zero towards 70 per cent nickel.

Regarded from another point of view, a depends on the proportions of the additional constituents contained in the alloy. The presence of manganese or chromium diminishes its value, that of carbon increases it, and it can be shown that a nickel-iron alloy containing no carbon whatever would be perfectly stable. We are justified in concluding from this that the instability is due to the slow transformation of cementite (Fe_3C); in fact, if a small proportion of chromium be added to a nickel-steel alloy, poor in carbon, the stability of the alloy is found to increase to such an extent as to become almost perfect; the chromium combining with the carbon and preventing the combination of the latter with the iron (Guillaume, 1920).

Until the discovery of the causes of instability had made its elimination possible, this defect had always prevented invar from being employed for the construction of reference standards, and had restricted its use either to standards of the second order or to auxiliary standards. Artificial aging (heating to a moderately high temperature, 100° C. for example, followed by extremely slow cooling) was found to reduce the instability considerably; and a knowledge of the laws of instability made it possible to adjust measurements by corrections which, if given precautions were observed, restricted any remaining uncertainties within narrow limits. The complete elimination of instability will, however, considerably extend the sphere of utility of this alloy.

§ (9) General Properties of the Nickel-steel Alloys.—The reversible nickel-steel alloys are extremely tough, and absolutely devoid of brittleness. In the "natural state" their elastic limit is not very high, but their deformations under mechanical strain are completed very rapidly, so that under a tensile test that part of the test-piece where the break would normally occur becomes very hard; the contraction is arrested, and tends to take place at some other point of the test-piece. In this way the test-piece becomes toughened uniformly throughout, and when rupture occurs, under a tension which may amount to 100 kg./mm.^{2} (about 60 ton/in.^{2}) with an elongation of 30 to 40 per cent, the test-piece has been uniformly reduced in sectional area and uniformly hardened. The presence of chromium, tungsten, or carbon raises the elastic limit. A very small proportion of manganese facilitates forging; when larger proportions are present, up to 5 or 6 per cent, castings may be taken.

Tempering softens the alloy. This process is sometimes resorted to in order to facilitate the operation of drawing. Alloys of typical invar, even when containing relatively high proportions of hardening admixtures, may be drawn into very fine wires (0·03 mm. being attained without difficulty).

The nickel-steels take a high polish, free from surface pores, if the alloy contains sufficient manganese and carbon. They are incomparably less oxidisable than ordinary steel. When the surfaces are well polished, lines traced on them with a diamond exhibit perfect clearness of outline.

II. Applications

The extremely small values, practically zero, of the coefficients of expansion α and the thermoelastic coefficients ϵ have given rise to numerous applications; as have also the anomalous values of β, the coefficient which regulates the curvature of the expansion curve. The practical uses to which invar and elinvar have been applied are indeed so numerous that it is not possible to give a full account of them here, and we will accordingly confine our attention to the most characteristic of these applications.

§ (10) Measurement of Geodetic Base Lines.—In geodetical surveying, every tri-

angulation starts from a base line: which is usually a line about 10 km. in length, and as straight as possible, measured at the surface of the earth. Until quite recently, the lengths of such base lines were determined by means of measuring bars, generally about 4 m. in length, which served to fix the respective distances between microscopes in alignment along the base, and were continually moved forwards so as to cover by successive stages the whole distance comprised between the terminal marks of the base line. As the measurements were made in the open air, the strictest precautions had to be observed in determining the temperature of the standard bar; and consequently the measurement of a base line was a long and costly operation.

A systematic examination of the results obtained by various previous observers enabled Edw. Jäderin, towards the year 1890, to devise a method and appropriate equipment for replacing the rigid measuring bars by wires stretched under a constant tension, which serve to determine the distances between fiducial marks set up along the base. These wires are usually about 24 m. in length. The number of spans is therefore only one-sixth of the number required when rigid bars are used, and as the apparatus is light and easily and quickly set up, only a few persons need be employed and rapid progress is attainable. When steel wires were used, the inevitable uncertainties respecting their temperature precluded any great accuracy of measurement. Invar was first substituted for steel in an actual operation in 1899, during the progress of the Russo-Swedish expedition for measuring an arc of the meridian at Spitzbergen. The successful result of this measurement led to an exhaustive investigation of the metrological properties of these wires being undertaken at the International Bureau of Weights and Measures by Benoît and Guillaume. An equipment specially designed for the use of invar wires now admits of an accuracy of one part in a million being attained,[1] and is so readily operated that an efficient staff of a dozen men can measure about 5 km. a day on good ground. With wires of appropriate length (a length of 168 metres has been attained) ravines and rivers may be traversed, which would be quite impracticable with rigid bars.

For the measurement of base lines, it is desirable to employ invar that has undergone special treatment, as referred to above, so as to have its expansibility brought very close to zero. Values of the order of 0·02 to $0{\cdot}03 \times 10^{-6}$ can be realised, so that it is almost superfluous to measure the temperatures of the wires.

[1] See "Surveying and Surveying Instruments," § (41), iii. Vol. IV.

In some countries, notably in the United State, narrow ribands or tapes of invar are used by geodesists, in preference to wires.

The very moderate cost now involved in the measurement of base lines makes it possible to increase the number of these as well as their length. Two important facts are to be recognised as resulting from this: in the first place, the calculation of the length of the first side of a triangle of the triangulation proper, in terms of a short base line, involved appreciable errors; whereas it is now practicable, in certain cases, actually to measure a side of the first triangle directly; secondly, the practice of superposing triangles over distances of hundreds of kilometres necessitated the highest degree of precision being attained in the measurement of angles, otherwise the errors introduced soon became excessive; while at the present day it is recognised in practice that triangles ought to be referred to a base line about every hundred kilometres.

The progressive and transitory changes to which invar is liable have made it necessary, up to the present, for certain precautions to be taken to safeguard the wires, that is to say, as regards wide variations of temperature.

In order to detect possible changes in the wires due to accidental causes, their lengths are determined from time to time, and particularly at the end of the summer field service. The amounts of the progressive changes are ascertained at the same time, which admits of their being eliminated. Measuring bases have been laid down in the principal metrological institutions for the purposes of these determinations.

In the absence of repeated comparisons, corrections to be applied to the initial values of the wires are available. These are based on a knowledge of the progressive changes determined in specimen pieces of invar which have been under investigation for many years.

The use of wires made of stable invar will obviate the necessity for some of the precautions which have to be taken when ordinary invar is employed.

§ (11) Compensation of Clocks.—The expansion of the rod of a pendulum under the influence of heat causes, for each degree centigrade, a diurnal retardation of about 0·5 sec. (in the case of steel).[2] Attempts have been made to get rid of this defect by means of compensatory devices, the best known being that of Graham, which consists in fixing, at the extremity of the rod, a cylindrical vessel made of glass or steel, containing a certain quantity of mercury. The mercury expands upwards and thus compensates for the downward displacement of the vessel containing it.

The ratio of the relative expansibility of mercury in steel or glass to the expansibility

[2] See "Clocks," § (3), Vol. III.

of steel is about 15 to 1. A ratio nearly identical with this exists between the relative expansibilities of bronze or iron and of a suitably chosen invar. It is therefore to be expected that by making the rod of the pendulum of invar and the bob of bronze or steel (or even cast iron) a perfect compensation can be attained.

Various methods have been devised for effecting this compensation. In one method, the bob, which may be hollowed out or not, is such that the distance between its centre of gravity and the surface resting on the regulating nut has (subject to a reservation which will be made directly) the same total expansibility as that of the rod (Guillaume, 1897). Or the bob may be hollowed out very considerably, for example, up to its centre, and rest on a sleeve composed of two hollow cylinders screwing into one another, so that the whole may be made of such a length that compensation is rigorously attained (Thury, 1897); or, again, between the bob and the supporting nut, two cylindrical pieces made of different metals may be interposed, such that their total length is always the same but is so distributed between the two pieces that the total expansibility has the required value (Riefler, 1899).

In *a priori* calculations of the compensation, it is of course necessary to take into account the expansion of the moving part of the suspension, which generally comprises steel springs; and when the pendulum is to oscillate in a case communicating with the atmosphere, regard must also be paid to the variation of the density of the air, which depends upon the temperature and the barometric pressure, and in itself gives rise to a slight compensation, since as the temperature rises the density of the air decreases, and thus the resultant force on the bob becomes greater, so that the period of oscillation is diminished. The necessity for the latter correction disappears if the pendulum is enclosed in a hermetically sealed case, in which the air is of constant density.

The possibility of modifying the expansibility of invar to any desired extent, and even making it zero, affords a means of dispensing altogether with compensation. In practice, however, it is found to be more advantageous to retain a very small expansion. Now, since β passes through its zero value precisely in the immediate neighbourhood of the minimum, it will be possible to select an invar such that the linear term and the quadratic term in its formula of expansibility are in the same ratio to the corresponding terms in the formula of expansibility of the compensating metal. In this way complete compensation at all temperatures will be arrived at; whereas Graham's compensation leaves a small quadratic residual, owing to the fact that in the case of steel and mercury this condition of equality of the ratios is not satisfied.

Another advantage of using an invar rod results from the fact that compensation is computed on the hypothesis that the temperature is uniform from top to bottom of the clock case, a condition which is not always realised. The resulting error is proportional to the expansibilities of the rod and of the compensating piece. The use of ordinary invar accordingly reduces this error to one-tenth of its value for the mercury compensation.

The instability of invar, within the limits indicated above, is of no great importance as regards pendulums. The changes of length being produced very slowly, the changes in the rates of clocks occasioned thereby belong to the same category as those which are determined by astronomical observations. The use of stable invar entirely dispels any fear of these changes.

§ (12) Correction of Dent's Error by the use of an Alloy for which β is Negative.—In 1832 it was discovered by Dent, a clockmaker in the City of London, that a chronometer furnished with a spiral spring and a compensation balance, the rim of which is made of steel and brass, will, if compensated for two definite temperatures, become fast at temperatures intermediate to these. If the rate is correct at 0° C. and 30° C., the diurnal gain at 15° C. is about two secs.

Auxiliary mechanisms have been devised for the purpose of eliminating Dent's error. One of the best known of these is the arrangement, due to Loseby, in which two small mercury thermometers with curved stems are fitted on the bimetallic rim in such a way that the movement of the mercury in the stems introduces an appropriate quadratic term in the compensating formula of the balance.

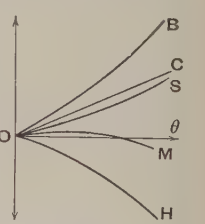

Fig. 11.

The cause to which Dent's error is due is clearly shown in *Fig.* 11. Compensation is rendered necessary by the change in Young's modulus for the spiral, which is represented by the curve OH. Again, the compensating formula of the balance is given by the difference between the expansibilities of brass, OB, and steel, OS. This difference is represented very closely by the straight line OC; and the algebraical sum of OH and OS is the curve OM, which represents Dent's error.

This error may be corrected simply by substituting for ordinary steel a nickel-steel

whose formula of expansibility contains a negative β, ONS, *Fig.* 12. The difference between this and OB is OC, which may be made exactly symmetrical with OH by a judicious choice of the relative values of α and β, and the assignment of suitable dimensions to the bimetallic rim. A nickel-steel containing from 42 to 44 per cent of nickel solves the problem (Guillaume, 1899).

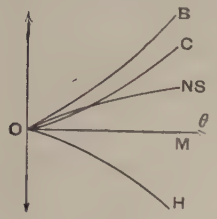

FIG. 12.

As the value of α for this nickel-steel is much smaller than for ordinary steel, its use in conjunction with brass makes the action more pronounced; which admits of either a shorter length or a greater thickness being employed. This tends considerably to reduce the effects of centrifugal force, which are quite appreciable with ordinary compensation balances. The regulation of chronometers is thus facilitated.

The new compensation balance has become widely known in chronometry, and has contributed greatly to its progress.

§ (13) APPLICATION OF ELINVAR TO THE COMPENSATION OF WATCHES.—Compensation would be unnecessary if the spiral were made of a metal for which Young's modulus was invariable.[1]

Now it will be seen from the curve A in *Fig.* 9 that the binary alloys furnish two approximate solutions of the problem, represented by the two points of intersection of this curve with the zero axis. As, however, these points correspond to a maximum and a minimum of the value of Young's modulus, both very pronounced, this will introduce a secondary error in the rates of watches, analogous to that of Dent, but of much greater amplitude; amounting, indeed, to from 20 to 25 secs. a day. But in watches which have a steel spring without any compensation device, the temperature error in the interval comprised between 0° C. and 30° C. is about 330 secs. a day; so that the use of a spiral of nickel-steel has an enormous effect in improving the rates of that class of watches whose price does not admit of their being fitted with a compensation balance. In point of fact, more than fifty million watches are now furnished with the compensating spiral.

The recent introduction of elinvar, properly so called, has enabled a still further advance to be made. For, if the spiral be constructed of an alloy for which, at ordinary temperatures, the value of Young's modulus is stationary in the neighbourhood of the maximum ordinate of the curve, complete compensation will then be effected by the spiral.

Chronometers fitted with the elinvar spiral made their first appearance in observatories (notably at Teddington) during the year 1920. Their regulation is a much simpler matter than that of chronometers fitted with an ordinary compensation balance. CH. E. G.

[1] More correctly, the changes in the rates of watches in which temperature is concerned depend essentially on variations of Young's modulus for the spiral, and also to a slight extent on the expansions of the spiral and the balance, acting in opposition to one another. Compensation will be complete when the change of Young's modulus for the spiral is such as to annul the very small residual left over by the expansions. It much simplifies the explanation, without modifying it in any essential respect, if the effect of the expansions is supposed negligible in comparison with that of Young's modulus.

INVAR STEEL: a nickel-iron alloy steel having a very low coefficient of thermal expansion. See "Steels, Special," § (50); see also "Invar and Elinvar."

INVARIANT EQUILIBRIUM, represented by horizontal lines. See "Alloys, Constitution of," § (1) (v.).

INVARIANT systems of alloys. See "Alloys, Constitution of," § (1) (iv.).

INVERSE RATE CURVES: a method of representing graphically the behaviour of a body undergoing change of temperature in which the two co-ordinates are (1) the temperature (θ) and (2) the times taken for the temperature to change through successive small equal temperature steps ($dt/d\theta$). See also "Metals, Thermal Study of," § (8).

IRIDIUM TUBE FURNACE, useful for temperatures up to 2000° C., where a strongly oxidising atmosphere is essential. See "Furnaces for Laboratory Use," § (2).

IRON, melting-point of pure, about 1500° C. See "Metals, Thermal and Mechanical Treatment of," § (1).

IRON-CARBON ALLOYS

I. PURE IRON

§ (1) PURE IRON is not a commercial product. Except when extremely careful precautions are taken, iron always contains a certain amount of impurity, even when prepared by an electrolytic method, and it is seldom obtained of greater purity than 99·9 per cent, while generally it is considerably less pure than this. Electrolytic iron has been manufactured by the electrolysis of a solution of ferrous and calcium chlorides at a temperature of 110° C., a current of about 20 amperes per square decimetre being suitable. The deposition is carried out on polished iron electrodes, from which the deposit may be

removed at the end of the operation. In the form in which it is obtained by this process it is very brittle and can hardly be deformed without cracking. This brittleness was usually attributed to the presence of occluded hydrogen in the metal, but in some cases the columnar structure of the deposit no doubt contributes to its weakness. In addition to being brittle, iron as deposited is, as a rule, considerably harder than ordinary annealed iron. The hardness and brittleness, however, can both be removed by suitable heat treatment.

Within recent years a brand of ingot iron of great purity has been put on the market. This is obtained by melting selected products in a basic open-hearth furnace, the metal thereby being obtained molten and cast into ingots in the ordinary way (hence the term ingot iron). The analysis claimed by the makers shows an iron content of 99·94 per cent, the impurities present consisting mainly of small quantities of carbon, silicon, sulphur, phosphorus, and aluminium.

§ (2) Microstructure.—An etched sample of commercially pure iron shows the characteristic polygonal structure of pure metals. When lightly etched the different crystals all appear white and are distinguished from one another by thin dark boundaries as seen in *Fig.* 1. When deeply etched the crystals

Fig. 1.—Pure Ferrite.

appear differently coloured and exhibit a distinct lustre. With still deeper etching and the use of a suitable etching reagent, etching pits or cavities appear in the surface of the crystals, and the shape of these pits indicates the cubic character of the crystallisation of the metal. The diagram, *Fig.* 2, shows diagrammatically the appearance of these pits. It will be noticed that they have the same shape and orientation in any one grain, but that the orientation in adjacent grains is different; sometimes the pits appear as triangular wedges when the section cuts the small cubes of a grain obliquely near the corner. The cubic character of the crystallisation of iron has been further illustrated by Osmond and Cartaud,[1] who succeeded by

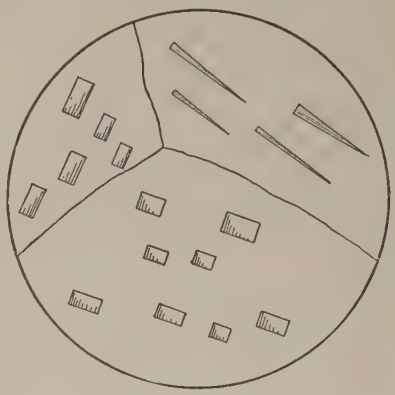

Fig. 2.

the reduction of ferrous chloride in obtaining crystals of iron in the form of perfect isolated cubes, while Stead [2] has also observed perfect cubes of phosphoretic iron.

The material of the polygonal crystals of commercial iron (and steel) is known to the metallographist as ferrite, a name suggested by Professor Howe. In commercial iron and steel the ferrite is not pure, but contains dissolved substances, of which the chief are silicon, phosphorus, and manganese. The characteristic properties of this constituent are, however, not altered, and the impure ferrite is not micrographically distinguishable from pure ferrite.

§ (3) Allotropy of Iron.—The study of the crystallography of iron is complicated by the changes which take place in the material at certain temperatures as it is cooled from its melting-point to ordinary temperatures or heated from ordinary temperatures up to the melting-point. Each of these changes is accompanied, in the one case, by the evolution of heat and a decrease, therefore, in the rate of cooling, or, in the other, by an absorption of heat and a marked decrease in the rate of rise of temperature.

We have reason to believe, from many considerations, that, within the range of the solid state of a substance, there may be various possible arrangements of molecules, or even of the atoms forming the molecules,

[1] Osmond and Cartaud, *Ann. des Mines*, 1900 [ix.], 18, 113.
[2] Stead, *Iron and Steel Inst. J.*, 1900, ii. 109.

corresponding to differences in the form or properties of the substance. These different conditions of the substance are known as allotropic forms, and corresponding to some, at any rate, of the marked temperature changes which take place when iron is heated or cooled, we have a number of allotropic forms or iron distinguished as α, β, γ, δ iron. The number of forms which exist is somewhat uncertain, and depends to some degree on the definition of allotropy which is accepted. Physicists and chemists, however, do not appear to be agreed as to the exact meaning of the term "allotropy"; some hold that in order to establish the existence of two allotropic forms in any metal, an evolution or absorption of heat must be shown when the metal in question is cooled or heated through its transformation point. Opinions differ, however, as to whether a well-defined change in some other single property constitutes a proof of allotropy or not; while some writers demand a crystallographic change at the temperature of transformation, particularly in discussing the allotropy of iron, others have excluded a change in the magnetic properties as evidence of allotropy.

The first definite evidence which established the existence of various forms of iron was provided by Osmond [1] when he discovered the existence of two thermal transformation points respectively at 760° C. and 900° C. To the variety of iron existing at temperatures above 900° C. he gave the name γ iron; that existing between 900° C. and 760° C. was called β iron, and that existing below 760° C. was known as α iron. The allotropic character of γ and α iron is now universally accepted, but considerable doubt has within recent years been expressed as to the difference between β and α iron, in spite of the fact that the heat evolution on cooling to 760° C. is always found. It is considered by some workers that the β transformation point is merely the end of the change from γ to α, lowered by undercooling, but the evidence in favour of this view is at present incomplete. The most marked change in the properties of the iron as it passes through the transformation point at 760° C. is that, whereas above that temperature it is practically non-magnetic, immediately below that temperature it becomes extremely magnetic. If such a sudden and perfectly discontinuous change in the properties of a metal can be advanced as evidence of allotropy, it must be conceded that β iron and α iron are physically distinct varieties. Within recent years evidence has been brought forward to establish the existence of another critical point in the neighbourhood of 1400° C. The iron existing between this temperature and the melting-point is known as δ iron, but its properties have not been studied.

It may be of advantage at this stage to trace the process of crystallisation in iron from the melting-point, and for this purpose reference may be made to *Fig.* 3, which represents a cooling curve of iron taken from 1600° C., at which temperature the metal is liquid, down to 0°. At 1530° C. a large arrest appears on the curve corresponding to the solidification of the iron and the production of what is presumed to be the δ form. At 1400° C. a small arrest indicates the transformation from δ to γ iron, and at 900° C. a larger arrest indicates the transformation of γ to β iron, the further transformation of which to α iron is indicated by a very small arrest at 760° C. Below this temperature no further transformations are observed. On reheating the metal these changes take place in the reverse order, but with this slight difference, that while the arrest point at 760° C. occurs on heating at the same temperature as it does on cooling, the arrest point near 900° C. takes place at a higher temperature on heating curves than on cooling curves. For this reason a nomenclature has been introduced to indicate whether the arrest point is obtained by means of heating curves or cooling curves. The arrest point at 760° is known as the A2 critical point, and that at 900° C. as A3 critical point. To distinguish between the arrests taken on heating and cooling curves the suffix R or C is added to the letter A (R indicating *refroidissement*, and C indicating *chauffage*). The exact temperatures at which these arrests occur have been investigated by Burgess and Crowe.[2] Using material of the highest obtainable purity and extremely delicate methods of investigation, they found that the A2 point occurred at 768° C. on both heating and cooling curves, but that while the AR3 point occurred at 898° C., the AC3 point did not occur until 909° C. Arnold maintains that the A2 point is in reality a double point, and that two peaks are found on a cooling curve if satisfactory apparatus is used, the upper peak being at 765° C. and the lower at 752° C. This statement is, however, not in accordance with the results

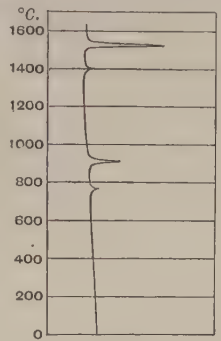

FIG. 3.

[1] Osmond, *Mémoires de l'artillerie de la marine*, 1887, xxiv. 573; *Iron and Steel Institute Journ.*, 1890, No. I.

[2] Burgess and Crowe, *Amer. Inst. Min. Eng. Trans.*, 1913, xlvi.

of other workers, and none of the 130 curves, for instance, taken with the greatest care and skill by Burgess and Crowe, show a double peak at AR2.

Many investigations have been carried out into the properties of iron in its different conditions, with a view to obtaining evidence for the existence of the different allotropic forms. Rosenhain and Humfrey[1] strained a bar of iron heated in such a manner as to give a temperature gradient whose maximum was above the A3 critical point. They found three distinct zones of deformation corresponding to the different varieties α, β, and γ iron. Ewen,[2] as the result of etching iron *in vacuo* at different temperatures, also claimed to have found evidence in support of the existence of all three varieties. On the other hand, while changes in the structure of iron on passing through the A3 point are generally admitted, few workers are able to record any microscopic evidence of a rearrangement of structure at the A2 point. For example, on reheating a piece of α iron through its critical point and quenching it at different temperatures no alteration of structure is found as a result of passing through A2, whereas passage through the point A3 invariably results in the recrystallisation of the β iron with the formation of new crystals of γ.

Dilatation of iron has been investigated by Benedicks and others, who note a very sharp discontinuity at the A3 point. Benedicks[3] also notes a slight continuously occurring contraction at the A2 point, although he does not regard this as sufficient evidence of allotropy. Burgess finds a marked change in the thermal E.M.F. at the A3 point, and a slight change at the A2 point. Rosenhain and Humfrey[4] have shown a distinct discontinuity in the tensile strength of iron at the A3 point, and a slight discontinuity at the A2 point, although the evidence for this latter change is not very strong. Their evidence shows, however, that γ iron at a temperature a little above its transformation point is considerably stronger than α iron. Meuthen reports discontinuities in the specific heat of iron at both the A2 point and the A3 point.

The most important contribution to the study of the allotropy of iron has been made by Westgren.[5] By means of an X-ray spectrographic examination of iron at various temperatures, he has been able to determine the actual space-lattices that exist within the different modifications of the metal. His observations possess the advantage that they are direct measurements made at temperatures at which the actual modifications occur, and they appear to settle conclusively the facts relating to the crystallisation of iron. It is shown that α iron and δ iron possess identical space lattices; this author's work confirms the determination of Hull that iron at ordinary temperature possesses a cube-centred cubic lattice, the edge of the unit cube being about 2·87 Å. In γ iron, on the other hand, the atoms are arranged on a face-centred cubic lattice, the size of the unit cube being about 3·65 Å. The character of the changes at 900° C. and 1400° C. is therefore well established; the change is one that involves a complete re-arrangement of the atoms, and recrystallisation in another crystalline form: these are certainly allotropic transformations. The crystallographic identity of the α and δ phases is, perhaps, surprising. Westgren was unable to find any crystallographic difference between the iron existing between 760° and 900° C., and the α or δ modifications. β iron, at 800° C., is shown by him to have a cube-centred cubic space-lattice, the cube edge being 2·92 Å., which is, within the limits of experimental error, identical with that of α iron, allowing for the thermal expansion. β iron must therefore be regarded as crystallographically identical with α iron, and if polymorphy is essential to allotropy, the change point at 760° C. is not an allotropic change. The so-called β iron problem cannot, however, be regarded as solved, since the spontaneous change in energy of iron at 760° C. in heating or cooling still remains to be explained.

[1] Rosenhain and Humfrey, *Roy. Soc. Proc.*, 1910, lxxxiii. A. 200.
[2] Ewen, *Internat. Zeit. f. Metall.*, 1913.
[3] Benedicks, *Iron and Steel Inst. J.*, 1912, No. II.
[4] Rosenhain and Humfrey, *Iron and Steel Inst. J.*, 1913, No. I.
[5] Westgren, *Iron and Steel Inst. J.*, 1922, No. I.

II. Wrought Iron

§ (4) Wrought Iron is a commercial iron free enough from carbon and other impurities to be malleable. It is manufactured by the reduction of iron ores and the refining of cast iron at a temperature so low that the product is never obtained completely molten, but in a pasty condition, and therefore mixed with a considerable amount of the slag formed during the operation. When the refining treatment of cast iron is carried out at a sufficiently high temperature to deliver the products in the molten condition, the refined metal is then free from slag and is known as steel. Wrought iron and steel may have identical composition except as regards the amount of slag, though, as a rule, steel contains more carbon and manganese, less silicon, and frequently less phosphorus than wrought iron. Wrought iron, as a rule, is practically free from carbon, but contains small amounts of the usual impurities, silicon, sulphur phosphorus, and manganese.

§ (5) Microstructure of Wrought Iron.—After the reduction process has been carried out in the puddling furnace in which wrought iron is manufactured, the hot pasty balls are withdrawn and subjected to vigorous forging and squeezing, as a result of which a considerable amount of slag is forced out and the particles of iron firmly welded together. Removal of the slag is, however, incomplete, so that when the wrought iron

is further forged or rolled down into billets and bars, the slag is drawn out in the form of long thin threads and appears as such in the finished product. The microstructure therefore consists of ferrite crystals in which are dissolved the silicon, phosphorus, and some of the manganese, a small amount of sulphide of manganese, a small amount of iron carbide, and a considerable quantity of slag. This latter constituent appears in longitudinal section in the form of many irregular black streaks, varying much in thickness and length, but all running in the same direction. In transverse section, however, the slag particles appear as small irregularly shaped dark areas and show no signs of the elongation due to rolling. When highly magnified, it is found that the slag in wrought iron frequently contains two constituents—a dark and a light one—the actual composition of which are uncertain. Their arrangement in the slag particles, however, strongly suggests that they had at one time formed a single homogeneous liquid and had only attained a separate existence after the solidification of this liquid had taken place.

Wrought iron is a very soft material, capable of being worked to a high degree. Moreover, it is very easily welded, and finds application in a large number of ways on account of this property. The dimensions of the ferrite grains of wrought iron are affected by the treatments, both thermal and mechanical, received by the metal, and have a considerable influence on its properties. The effect of such treatment will be considered in connection with the microstructure of mild steel.

III. Iron-carbon Alloys—Steel

§ (6) Iron Carbon.—Molten iron will dissolve carbon very readily up to a certain limit. A saturated solution at 1400° C. contains about 6 per cent of carbon, and at higher temperatures the amount in solution can be increased, but it is extremely difficult to get more than about 6 per cent to dissolve. Carbon can exist in solid iron in three different conditions:

(i.) As free graphite.
(ii.) As a compound of iron and carbon having the formula Fe_3C.
(iii.) In solid solution.

The actual relation between these three different forms of carbon and the iron itself is by no means clear in all respects, and the complete diagram representing this relation has not yet been prepared. Iron and iron carbide, which we find in practically all of the iron-carbon alloys, form a eutectic series with one another, which is shown in *Fig.* 4. The effect of the addition of carbon to iron is to lower its melting-point, as is indicated by the line AB. So long as the amount of carbon present does not exceed 4·3 per cent, solidification takes place by the separation of crystals of iron which contain more or less carbon in solution. Under conditions of equilibrium about 1·8 per cent of carbon are dissolved in the solid iron when the eutectic temperature is reached, but beyond this concentration the last stages of the solidification consist in the deposition of a eutectic of iron containing dissolved carbon and the carbide of iron Fe_3C. The eutectic line EC is shown in *Fig.* 4. To the solid solution of iron containing dissolved carbon

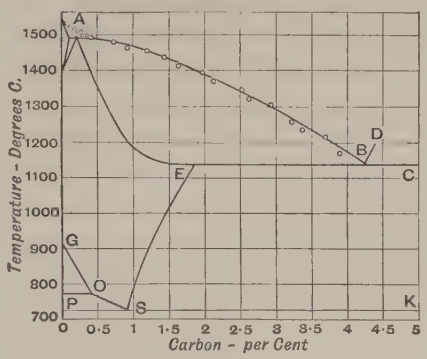

Fig. 4.

the name austenite has been given, while to the carbide Fe_3C the name cementite has been given. For concentrations of carbon exceeding 4·3 per cent solidification takes place by the deposition of primary crystals of Fe_3C, which separate until the residual liquid reaches the concentration B, when it solidifies as the iron-cementite eutectic.

The above diagram shows the relation between iron and iron carbide, but does not completely represent all that happens during the solidification of iron carbon alloys. The facts that slowly cooled cast iron contains practically the whole of its carbon in the form of graphite, and that cementite, or steel rich in carbon, deposits graphite when heated under certain conditions, do not receive recognition in the equilibrium diagram just described.

It is held by some workers that equilibrium is only reached in the iron-carbon alloys when the iron carbide is completely dissociated and the constituents present are iron and graphite. It has been suggested therefore that in addition to solidification according to the diagram given in *Fig.* 4, separation may take place with the formation of primary graphite and a graphite-austenite eutectic, and some writers, notably Charpy and Grenet,[1] Heyn,[2] and Benedicks recommend the use of metastable solidification curves in the equilibrium diagram of iron carbide

[1] Charpy and Grenet, *Bull. Soc. d'Encouragement*, 1902, p. 399.
[2] Heyn, *Elect. Zeits.*, 1904, x. 491.

alloys. *Fig.* 5 shows the diagram due to Benedicks. Along the line AB austenite separates out from solution, along the line BD graphite separates out from solution, while the line ABC represents the separation of a eutectic consisting of austenite and graphite. The lines AB′ and B′D′ represent respectively separation of austenite and cementite, while the line E′B′C′ represents the separation of the austenite-cementite eutectic. According to this diagram the iron graphite system is the stable one, and separation according to the iron cementite system only takes place through undercooling of the liquid during solidification. The line αE in this diagram represents the solubility of graphite in austenite, and the line E′S represents the solubility of cementite in austenite. Benedicks has advanced evidence in support of the position of the line αE, and considers that this offers confirmation of the existence of the stable iron graphite diagram. On the other hand, the possible existence of iron carbide

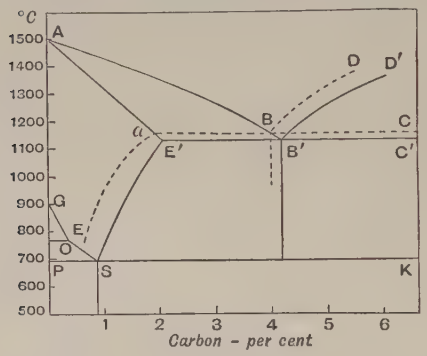

Fig. 5.

in his alloys was not excluded, and it seems somewhat strange that the lines BD, αC, and αE should so nearly coincide with the lines B′D′, E′C′, and E′S. While it is recognised that graphite is formed under certain conditions by the dissociation of cementite, and that under these conditions it is the stable form of carbon, there is considerable doubt as to whether it ever separates directly from solution. In ordinary castings, it appears to be certain that graphite only separates from solid cementite, and no evidence has been produced which offers clear proof that graphite exists as a primary separation under any conditions of solidification.

§ (7) The Equilibrium Diagram.—Of the determinations of the equilibrium diagram of the iron - carbon system, that due to Carpenter and Keeling[1] is perhaps the best known. This is given in *Fig.* 6. According to them iron-graphite is the stable system at high temperatures, although separation sometimes takes place according to a metastable iron-cementite system; at a temperature lower than that of the eutectic (the line EF) recombination of the graphite and austenite takes place with the formation of cementite.

[1] Carpenter and Keeling, *Iron and Steel J.*, 1900, No. II. p. 311.

More recently Rosenhain has plotted the experimental results of Carpenter and Keeling, of Gutowsky[2] and of himself, and obtained

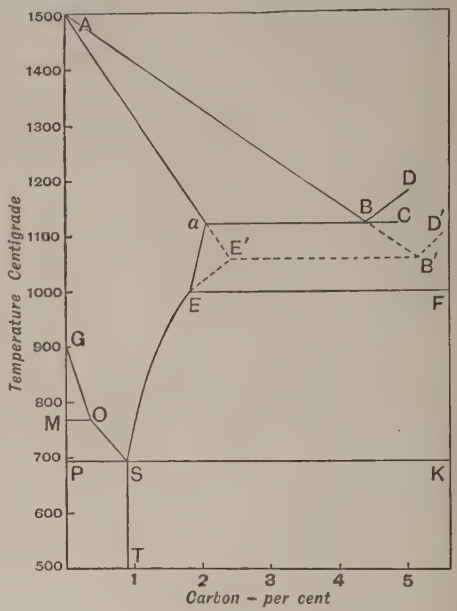

Fig. 6.

the diagram shown in *Fig.* 7. In this diagram the iron-cementite system is shown in thick lines, and the temperature of its eutectic

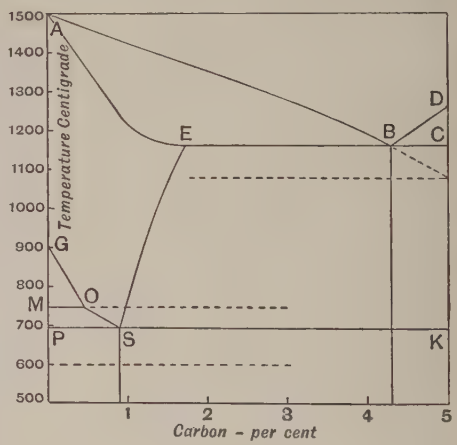

Fig. 7.

point is higher than that of the iron-graphite eutectic. This diagram does not indicate any recombination of iron and graphite once dissociation has taken place. The special

[2] Gutowsky, *Metallurgie*, 1909, vi. 731.

feature of Rosenhain's diagram is the shape of the solidus curve of alloys forming solid solutions. This is based on the work of Gutowsky and of himself, in which the Heycock and Neville quenching method of investigation was used in preference to the ordinary method of thermal curves. It is very probable that the curved form of solidus shown is much more accurate than the straight line indicated by most other workers. Referring to *Fig.* 4 we will consider the effect of carbon on the critical point of solid iron. As in the case of the melting-point, the position of the point A3 is lowered from about 900° C. by the addition of carbon until the temperature of 760° C. is reached. This lowering is produced by about 0·4 per cent of carbon. The A2 point in iron, however, appears to be unaffected by the addition of carbon, so that at this temperature the A3 and A2 points of iron-carbon alloys meet, as is shown in the point O. With further addition of carbon to the alloys, the transformation point is still lowered along the line OS, until it meets the line ES, representing the solubility of the cementite in austenite at the point S. The line GO therefore represents the temperatures at which β iron begins to separate from austenite and the field GMO represents the compositions and temperatures at which β iron exists as a stable phase. The horizontal character of the line MO suggests that carbon is practically insoluble in β iron; separation of β iron over the transformation range therefore results in the concentration of the whole of the carbon of the alloy in the untransformed γ iron. The line OS represents the direct separation of α iron from austenite, since below the temperature of the line OM β iron is unstable. The field MOSP therefore represents the conditions under which α iron and austenite exist together in the alloys. In the field GOESA the iron consists of a homogeneous solid solution from which cementite separates along the line SE. At the point S, therefore, we have the intersection of the lines of separation of ferrite on the one hand and cementite on the other hand. This, therefore, is a eutectoid point and the line PSK is the eutectoid line along which separates a eutectoid consisting of ferrite and cementite. To this eutectoid the name pearlite has been given on account of its "pearly" appearance on an etched specimen. The behaviour of several alloys, containing different percentages of carbon, may now be examined as they are cooled from a temperature at which they are liquid to one below the line PSK. The steel containing 0·3 per cent carbon will undergo the following transformations. Freezing commences at 1480° C., after which it will consist of a homogeneous solid solution in which the whole of the carbide is dissolved. At 820° C. β iron begins to separate from the alloy and continues to do so until a temperature of 760° C. is reached. At this temperature the separated β iron transforms into α iron, and further separation of α iron then takes place from the untransformed solid solution until a temperature of 690° C. is reached, when the residual solid solution decomposes into a mixture of ferrite and cementite. The microstructure of such a specimen is shown in *Fig.* 8, in which the light part represents the pure ferrite and the dark part represents the eutectoid mixture of ferrite and cementite. With an increase of the carbon content to 0·7 per cent the points AR3 and AR2 coincide, and only one arrest point is found on the cooling curves to indicate separation of α iron from austenite. The microstructure of such a sample, after passing through the transformation range, is shown in *Fig.* 9. The amount of ferrite is here much less than in the previous sample and the amount of pearlite is correspondingly increased. The eutectoid alloy which contains 0·9 per cent carbon consists entirely of an intimate mixture of ferrite and cementite, which are formed from the solid solution austenite at the point S.

FIG. 8.—Ferrite-pearlite. Carbon, 0·3 per cent.

The character of the eutectoid pearlite is particularly well shown in *Fig.* 10, which is taken from a sample in which this constituent is very coarse. It is seen to consist of plates of the compound cementite in a matrix of ferrite, and in the present instance the cementite plates are sufficiently thick for their character to be clearly seen. Usually in steel the plates of cementite are so thin that it is not possible, even under the highest powers of the microscope, to magnify them

sufficiently to see that they really are thin films of a light etching constituent; they are usually so thin that they merely form slight rounded irregularities in the polished surface,

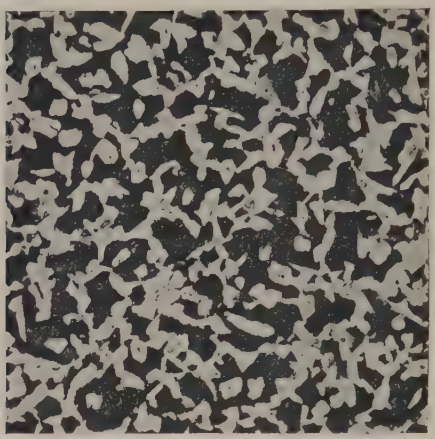

FIG. 9.—Ferrite-pearlite. Carbon, 0·6 per cent.

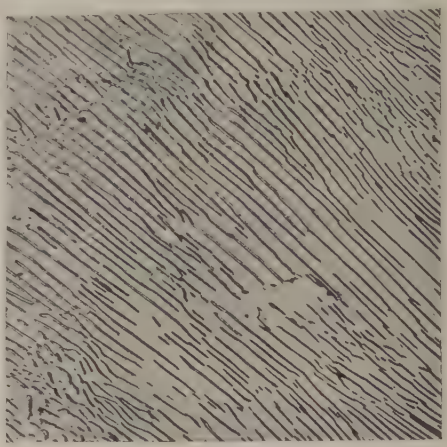

FIG. 10.—Pearlite.

and appear as thin dark lines under the microscope. When magnified sufficiently, the dark areas shown in *Figs.* 8 and 9 would have this typical eutectoid appearance.

With still higher percentages of carbon the alloys contain more than sufficient cementite to form pearlite with the ferrite of the alloy, and some appears as a primary separation from the austenite, in much the same manner as ferrite has been shown to appear. In this case the line SE indicates the beginning of the separation of cementite, which is indicated by an arrest on cooling curves, the point being known as the A*cm* point. A photomicrograph of an alloy containing 1·2 per cent carbon is shown in *Fig.* 11. The cementite appears as a network surrounding grains of pearlite. When the amount of carbon exceeds 1·8 per cent the type of microstructure is somewhat different, although the constituents of the alloys are the same. Beyond this point cementite separates directly from the liquid steel as a constituent of the eutectic, the other constituent being austenite saturated with cementite; since, however, the solubility of cementite in austenite falls steadily as the temperature falls, deposition of this constituent continues, as has already been indicated. We have therefore to distinguish, in high carbon alloys, two methods of separation of the constituent cementite.

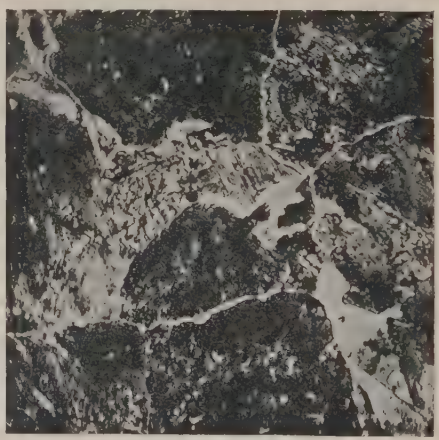

FIG. 11.—Cementite-pearlite.

The structural changes which take place when steel passes through its critical range have an all-important influence on the properties of the metal, and the extended use of steel largely depends on the accurate control of the structural changes which take place. Moreover, a sample of steel may be ruined for its purpose by apparently trivial differences in treatment; it is therefore of importance to know not only the constituents of steel, but the manner of their arrangement in the metal, on which the properties of the product depend to such a large extent.

§ (8) CAST STEEL.—It is essential that we should first consider the structure of cast steel, that is, steel which has been allowed to cool from the liquid state without any subsequent thermal or mechanical treatment. The ordinary size of steel ingots greatly exceeds that of any other metal, and it would therefore be expected that it would be particularly liable to all the ills to which castings in general are heir. This

is to a large extent correct, and the difficulties in obtaining sound castings are very great. Given a sound casting, however, heat treatment can be used which will to a large extent remove the undesirable properties which are so frequently associated with castings.

We are indebted to Belaiew, more than to any one else, for our knowledge of the crystallisation of steel. According to him the primary crystallisation consists in the formation of dendrites of a solid solution of iron and carbon (austenite), all steels immediately after solidification being built up of juxtaposed and interlocking dendrites mutually limiting each other. These dendrites are composed of octahedra, the crystalline form of γ iron. Immediately after solidification is complete a crystalline transformation sets in, which Belaiew calls granulation. This granulation continues until the critical range is reached, when the metal consists of a number of grains, each being built up of octahedra and having its own orientation. There is no very obvious reason why "granulation" should take place in a metal immediately it has become solid, and it probably indicates some unknown change in the material in this range. It is quite possibly connected with the critical point which occurs at about 1400° C. in pure iron, but about which very little is known. Generally speaking, the slower the cooling, and the longer the time which the metal is kept in the granulation zone, the coarser the austenite grains on reaching the critical range.

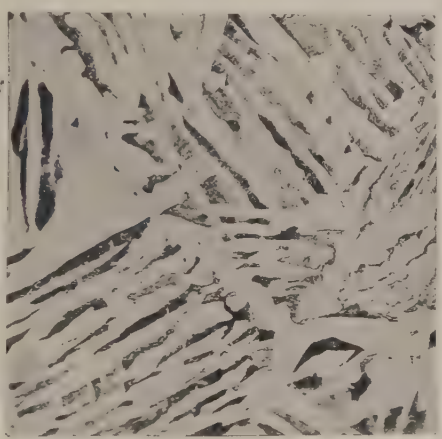

FIG. 12.—Widmanstätten Structure in Mild Steel.

In passing through the critical range the excess ferrite of steels containing less than 0·9 per cent carbon (known as hypo-eutectoid steels) and the excess cementite of steels containing more than 0·9 per cent carbon (hyper-eutectoid steel) is rejected by each austenite grain, until finally, in cooling through the point $Ar1$, the remaining portions of each grain, now necessarily of eutectoid composition, are converted bodily into pearlite. This decomposition of the austenite may be called the secondary crystallisation. Very slow cooling through this range promotes the separation of the ferrite or cementite in the crystal boundaries of the austenite grains, giving rise to a cellular or network structure, in which the excess constituent, ferrite or cementite, is arranged as envelopes surrounding pearlite grains. If, however, cooling is rapid, there is not sufficient time for the necessary diffusion of these constituents towards the boundaries of the grains, and they are largely precipitated between the cleavages of the existing crystals. The structure thus produced, which is illustrated in *Fig.* 12, is known as the Widmanstätten structure, in memory of A. Widmanstätten, who first discovered it in meteorites. In castings the conditions are very favourable to the formation of this structure, on account of the large size of the crystals, since under these conditions diffusion is seldom sufficiently rapid to preserve completely the cellular type of structure. The ferrite lines cut one another at definite angles in any one crystal, and the arrangement of these lines affords a weighty proof of the octahedral character of the austenite crystal.

From the foregoing it will therefore be seen that long exposure to high temperatures, since it promotes the growth of large crystals, favours the precipitation of ferrite or cementite in the cleavage planes; rapid cooling through the critical range has the same effect. Short exposure to high temperature and slow cooling both favour the cellular type of microstructure.

Because of its coarse structure cast steel is less tenacious and less ductile than forged or properly annealed steel of the same composition. Steel, however, differs from many other metals and alloys in that it possesses critical points, at which changes in the crystalline arrangement take place, and the existence of these critical changes enable one largely to remove the mechanically weak properties of the casting. The coarse crystals of most cast metals are extremely stable, and cannot be broken up simply by heat treatment. Unless the metal is deformed by mechanical work, either when the metal is hot or cold, it is impossible to disturb the coarse crystalline structure of the casting, which is accompanied by poor mechanical properties. It has already been indicated in what manner the structure of a steel casting can be modified by thermal treatment during the first cooling from the

liquid state: this can influence the properties to a moderate extent, but much more profound changes can be effected by suitable treatment subsequent to the first passage through the critical point. If a steel casting be reheated, no change takes place until the critical point A1 is reached; at this temperature, however, the pearlite transforms into homogeneous austenite, which, as the temperature is raised, absorbs the excess ferrite or cementite until, when the upper limit of the transformation range has been passed, the whole alloy consists of homogeneous solid solution. When this transformation begins it takes place from a large number of centres, with the result that the steel, instead of consisting of a few coarse crystals, as it did in the cast state, is composed of a large number of small crystals. At this temperature, however, crystal growth can proceed with appreciable speed, and growth of some of the crystals can take place at the expense of others; the actual size of the structure will therefore depend on the extent to which the critical range is exceeded and the time which the alloy is held above the range. Unless, however, the steel is heated for a long time at a temperature considerably above its critical range, the structure which results from this treatment is very much smaller than that of the casting. If now the material be cooled through its critical range again, the decomposition of the austenite again takes place, but the smaller original structure leads to a much more intimate mixing of the constituents than can ever be obtained in an untreated casting. Thus it is seen in what manner the existence of the transformations in these alloys permits the metallurgist to modify the structure. The treatment required to give the best results will depend to some extent on the original condition of the casting; for example, in a large casting the arrangement of the ferrite and pearlite may be so coarse that considerable time must be given on reheating to ensure complete diffusion, and during this time growth of the austenite crystals will proceed, so that the refining of the structure is not sufficient; in such a case the process may be repeated. The treatment of steel castings is perhaps more difficult than steel forgings, but there is no reason why they should not be so modified by suitable manipulation as to give results little inferior to those obtained from forgings and other worked material. Other properties of steel castings, which depend on the presence of impurities, from which steel is never free, will be described later.

§ (9) The Mechanical Treatment of Steel. —Forged steel articles are manufactured by submitting the cast material to mechanical pressure by means of rolls, presses, dies, or hammers, usually followed by special heat treatment. We have therefore to consider the effects of mechanical treatment and of heat treatment on the alloy, whether they be carried out as separate operations or whether they form one manufacturing process.

While the primary object of working steel is to modify its shape, it has also profound influences on its other properties which require consideration. In some cases these properties are modified in a manner so beneficial that articles which could be produced more readily in the form of castings are made by forging operations, with the object of obtaining a better article.

In the first place, work may influence the properties of steel in a manner which is independent of the constitution. Practically all steel castings are unsound, and contain defects such as blowholes, while, as will be seen later, they are specially liable to be "cored." Mechanical deformation usually closes up the blowholes, and in some cases actually welds them up, and it can usually be so arranged that it leaves the resulting defects in a position or condition in which they will have a less deleterious effect than they would in a cast article.

Work has varying effects on steel according to the temperature at which it is applied. The effect of cold work is very similar to that on other metals; in the case of hot work, however, the effect varies considerably according to whether it is carried out above, within, or below the critical range of the steel. Hot work may be applied simply with the object of modifying the shape of the article, and without regard to its final mechanical properties, in which case it is immaterial at what temperature it is applied, so long as it is not carried out at a temperature which will of itself ruin the material, or in such a manner as to lead to the rupture of the metal. Usually in such circumstances a high temperature is adopted, since steel is softer at high temperatures than at low temperatures, and requires less power for its deformation. If, however, work ceases while the metal is still above its critical range, it is evident that the austenite crystals will have an opportunity of growing, and the resulting grains will be the larger, and the final structure the coarser, the higher the temperature at which work was stopped. If a subsequent heat treatment is to be applied the forging temperature is not of great importance.

On the other hand, there are many commercial operations in which hot working of steel is not followed by subsequent heat treatment, and this applies in particular to many rolling operations. It is, in such cases, of the greatest importance to secure that the metal shall receive its final mechanical deformation at such a temperature that it will possess

good mechanical properties. The finishing temperature, as the temperature at which work ceases is called, should not be below the $Ar3$ point of the steel, nor so far above it that there is time for the growth of coarse austenite grains in the metal. The suitable arrangement would be to finish when the metal was but a few degrees above the critical range, while in many cases, especially with hyper-eutectoid steel, the process might be continued with advantage to a few degrees above the $Ar1$ point. It is not advisable to continue to work steel after it has passed through its lower critical point, since the structural distortion of the pearlite remains in the finished product, and may be harmful. In most works much attention is now given to the control of finishing temperatures, especially in regard to rolling operations, such as the production of steel rails, where the grain size of the product may be reduced to a minimum and the physical quality appreciably improved.

The cold-working of steel has the same general effect as in the case of any other metal; the material is rendered harder and stronger, but more brittle. For many purposes cold working is resorted to in manufacture, with very useful results. It is, however, very dangerous to use cold-worked steel under certain circumstances, since, although the effect of work is to increase the elastic limit in the direction in which the work was applied, yet it renders the material much more liable to failure under alternating stress. When the article is only required to carry a stress in the direction of working, the process is of great use. For example, in the case of steel wires for stranded wire ropes, or piano wires, cold-worked material may be used. The effect of the cold work on the structure of the wire can readily be understood. It causes a deformation of the ferrite crystals and an elongation of the pearlite. As will be shown later, there is a further danger in using cold-worked material since under certain circumstances a coarse crystalline structure will be produced by subsequent annealing operations, and lead to undesirable mechanical properties in the resulting product.

§ (10) The Annealing and Heat Treatment of Steel.—The annealing and heat treatment of steel form a very important part of the manufacturing processes in articles made from this alloy. It is seldom that steel, after mechanical treatment, is in a suitable condition to be put into service, and some form of heat treatment is frequently applied.

The purpose of heat treatment may be simply to increase the softness of the material and render it more suitable for further forging operations; it may be simply to remove the ill effects of cold work; it may be to secure a desirable combination of high strength and ductility, or it may be to secure the greatest amount of hardness irrespective of the other properties of the steel. These and other objects, which are not capable of such ready control in most metals, require very careful manipulation of the conditions at all stages of the treatment.

The annealing and heat-treating operations may be considered under the following heads: (i.) the heating of the articles; (ii.) the maintenance of the required temperature conditions; (iii.) the cooling of the articles; (iv.) the process of annealing.

(i.) *Heating.*—Heating for annealing may be carried out in any of the usual types of furnace, either gas-fired or electric; in many cases, however, steel articles are of such a great size that all parts of them cannot attain the required temperature simultaneously. It has, for example, been shown that in a solid forging a foot thick the centre frequently reaches its annealing temperature, with ordinary methods of annealing, about an hour after the outside portions. This temperature gradient cannot be altered without the use of rates of heating so slow as to be impracticable on a commercial scale, and it is perhaps unfortunate that steel, which is used largely in massive forms, is a somewhat bad conductor of heat, since this favours the setting up of a steep gradient in the metal. While this temperature gradient is serious, it may be still more serious if due precautions are not taken, and the outer parts of a forging may be ruined before the inside has reached the required annealing temperature. Further, in some cases forgings and castings which have different sections in different portions have to be treated, and it is difficult, if not impossible, to ensure that the thin sections do not exceed the annealing temperature in bringing the thicker parts to this point. The usual method which is adopted with large articles is to place them in a furnace which is slightly hotter than the required temperature; the heat supply to the furnace is so regulated that the temperature of the article and of the furnace approach one another and, under ideal conditions, become identical at the annealing temperature. Thin sections may be to some extent protected during this operation by preventing them from coming into direct contact with flame or from direct radiation from the walls, or by similar means

(ii.) *Maintenance of Temperature.*—The article must be kept at its annealing temperature for a time sufficiently long to attain a uniform temperature throughout. Heating beyond this period will depend on the effect which it is desired to produce in the steel, and must be considered separately in each instance; but it has already been shown that where refinement of structure is aimed at by passage through the critical point,

the time at the annealing temperature should not be prolonged. For other purposes, however, some of which will be indicated later, long periods are necessary. It is also obvious that, in operations where the exact temperature is of such importance, pyrometric control is desirable.

(iii.) *Rate of Cooling.*—Where the temperature of annealing is below the Ar1 point of the steel the rate of cooling has but little effect on the resulting article, except when it is sufficiently rapid to lead to the production of internal stresses through more rapid rates of cooling of some parts than of others (this is not true of certain special steels, where the rate of cooling below the critical range is very important). When, however, the annealing temperature is within or above the critical range, the rate of cooling is of the greatest importance, and has a profound influence on the resulting properties of the material.

(iv.) *Annealing.*—In the first place, we will consider the effect of annealing different qualities of steel when the annealing temperature is above the critical range, and will indicate the effects both of annealing temperature and rate of cooling. In the case of hypo-eutectoid steel, as the temperature is raised the pearlite becomes transformed into austenite when the critical point Ac1 is passed, and as the temperature is raised above this point the excess of ferrite is absorbed, until, when the upper limit of the transformation range is passed, the metal consists wholly of austenite crystals. These, as we have seen, are at first small, but their size increases as the temperature is raised and as the time of annealing is increased. On cooling down no change takes place in the constitution of the alloy until the point Ar3 is reached, when, if the rate of cooling has not been too rapid, α or β iron begins to separate from the solid solution, which process continues until the eutectoid transformation occurs. The manner in which separation of the ferrite takes place depends both on the size of the austenite crystals—that is, on the time and temperature of annealing—and on the rate of cooling. In the first place, the number of centres at which separation takes place depends on the rate of cooling: if this be rapid, precipitation takes place at a large number of centres in an endeavour to preserve constitutional equilibrium; if cooling is slow, equilibrium can be preserved by the slow separation of this constituent at relatively few centres, towards which diffusion of the excess of the constituent can take place during the cooling operation. The number of centres of crystallisation depends then on the rate of cooling. If, now, the crystal structure of the austenite is small, and the amount of ferrite is large, the growing ferrite areas finally become large compared with the original austenite crystals, of whose orientation no indication remains. In the case of a steel containing 0·2 per cent carbon, for example, a structure similar to that shown in *Fig.* 8 is found. If, however, the amount of ferrite which separates is small, as in steels containing not much less carbon than the eutectoid, there is a distinct tendency for the ferrite to take up its position in the grain boundaries of the austenite, with the result that a cellular arrangement of the ferrite is obtained in the alloy. In the event of the austenite grains being large, as a result of overheating, the ferrite particles separate partly along the cleavages of the austenite crystals, and give a structure similar to that shown in *Fig.* 12, which represents the steel of the same carbon content as that shown in *Fig.* 8, with the sole difference that it has been annealed at a higher temperature. In this case very much slower rates of cooling would be required to produce the cellular type of separation. With hyper-eutectoid steels the same argument applies, with the difference that in this case the constituent which separates is cementite. Since, however, this constituent is never found in such large quantities as the ferrite of low-carbon steels, and since its range of separation is larger (its limit of solubility is indicated by the line SE in *Fig.* 4), there is a greater tendency for the cellular type of structure to be formed, and relatively rapid cooling is necessary to obtain in it the angular needle-like form frequently associated with ferrite. It does not necessarily follow that the cellular structure found in these alloys indicates exactly the size of the austenitic grains which existed at a high temperature in the metal; it is quite conceivable that at many of these grain boundaries separation of ferrite or cementite would not take place, in which case they might be hidden in the final product. There is, however, no doubt that a coarse cellular or acicular structure indicates a coarse-grained structure when the steel consisted entirely of austenite.

In the case of steel of eutectoid composition there is no "primary separation" during the critical change, and the relation between the final structure and the structure at a high temperature is not so clear; frequently steel of this composition consists of physically distinct "grains" of pearlite, clearly distinguishable from one another, but it is by no means certain that the size of these grains is not determined more by the rate of cooling through the critical point than by any previous annealing treatment.

A process of annealing which has attained a very general application consists in heating steel to a temperature a little in excess of its Ac3 critical point (not more than 50° C. above), followed by cooling in air. It is found

that in most cases this gives a uniform fine structure, with which are associated mechanical properties of a high order.

When the rate of cooling is increased, a point is reached when a difference can be observed in the structure of the steel. Ferrite (or cementite) requires time for its separation,

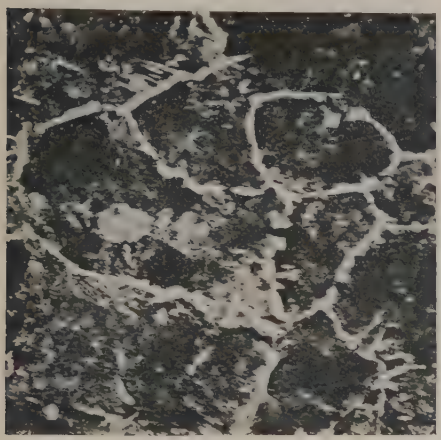

FIG. 13.—Ferrite-sorbite.

and when the rate of cooling reaches a certain value, which depends on the composition of the alloy, separation of the massive primary ferrite is not complete when the eutectoid transformation occurs. *Fig.* 13, for example, shows the same piece of steel as *Fig.* 9, cooled at a more rapid rate. The amount of ferrite is obviously smaller when the rate of cooling is sufficiently great. It also follows that the composition of the dark etching grains is not now that of the true eutectoid, but that it contains more iron. On examination under high power it may often be found to possess the typical lamellar structure of pearlite, and may then be regarded as a " diluted " pearlite. The removal of free ferrite from the alloy in this manner has a strengthening effect, but reduces the ductility to some extent. Frequently, however, and always if the rate of cooling be increased still more, the " pearlite " cannot be resolved under the highest available powers of the microscope. In this condition it has been given the name sorbite, in honour of Dr. H. C. Sorby, the earliest worker in ferrous metallography. Its properties are not clearly defined from pearlite, into which it frequently merges in one and the same alloy, but it is distinctly a harder, stronger, and less ductile constituent of the metal. It must be regarded as essentially a mixture of ferrite and cementite, in which time has not been given for the particles to attain a size sufficiently great to be separately visible under the microscope.

This constituent may be found in steel of any composition, and may have a carbon content containing up to 1·8 per cent. Its properties are therefore not very definite in character.

With still more rapid rates the suppression of the structural changes which take place on slow cooling becomes more complete. When the steel is cooled very rapidly, as by dipping it into water, an entirely different structure is produced, an example of which is shown in *Fig.* 14, which represents the structure of steel containing 0·5 per cent of carbon which has been quenched from about 1200° C. This temperature has been used in order to obtain a coarse structure, since a quenching temperature near the Ac3 point gives a structure in which the details are not readily seen. In this structure the outlines of the austenite grains are traceable, but, instead of the normal polygonal structure of a homogeneous solid solution, such as one supposes to exist at the quenching temperature (and which has been proved to exist by other evidence), we find that the grains are covered with a tracery of markings, not very distinct in their outlines. These markings make angles with one another which are found to be similar to those of the

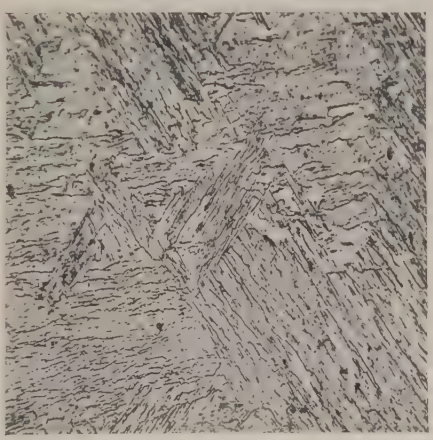

FIG. 14.—Martensite.

ferrite in cast or overheated steel, and which correspond with the cleavages of the austenite crystals. When the carbon content is high (about 1·0 per cent or more) the structure does not as a rule consist wholly of this acicular structure, but is partly composed of structureless areas as is shown in *Fig.* 15. In this alloy the dark etching portions are identical with the constituent of *Fig.* 14. The light portions in this case are the constituent austenite, preserved by rapid cooling, but it is never found possible, in ordinary steels, to preserve

the alloy completely in this form. It is always accompanied by a certain amount of the acicular structure, which is called martensite. This latter constituent is extremely hard, and is the constituent which confers its remarkable hardness on quenched steel. Its constitution will be considered later.

When the rate of cooling through the critical

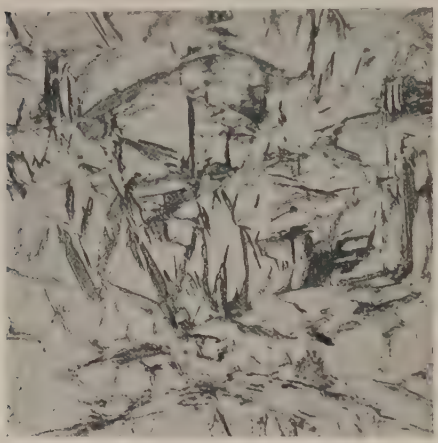

FIG. 15.—Austenite-martensite.

point Ar1 is rather less than that which is sufficient to preserve the alloy wholly as martensite, another constituent is sometimes found, usually accompanied by martensite, though sometimes alone in the alloy. This is shown in *Fig.* 16, where it appears as black etching areas, the light portions being martensite. This constituent, while harder than sorbite, is not nearly so hard as martensite. It has been given the name troostite. In many ways its properties are similar to those of sorbite, and it has been shown to be similar to it in constitution. The work of Benedicks has shown that its properties can be explained on the assumption that it is a very fine mixture of ferrite and cementite, and he has compared it with a colloidal solution. It appears to be different from sorbite mainly as regards the state of division of the ferrite and cementite particles.

Recent investigations into these constituents of steel have thrown light on their method of formation. It has, for example, been found, by taking cooling curves actually during the cooling of steel samples at different rates, that when the critical points occur at their equilibrium temperatures, the ordinary structures, consisting of ferrite and pearlite, are found. When, however, the rate of cooling is increased to such an extent that the critical points occur at lower temperatures, the intermediate structures which have been indicated are formed. For example, sorbite is produced when the transformation temperature is but little lowered; troostite is found in the specimens when the transformation point occurs below 650° C. but above 350° C.; martensite is only produced when the temperature of transformation is lowered to below 350° C. It is of special importance to note that the formation of martensite is accompanied by an arrest on the cooling curve of the alloy, since it indicates that the transformations are not wholly suppressed. The constitution of this constituent will be specially considered later.

Annealing of steel may be carried out for purposes other than the refining of the structure. When it is simply designed to remove the hardness due to cold-working it is not necessary that the lower critical point should be exceeded; in fact, if the maximum softness is required in the alloy it is better to anneal a little below the Ar1 point. The temperature at which recrystallisation of mechanically deformed material begins depends on the amount of deformation, and is the lower the greater the amount of deformation. In severely deformed iron recrystallisation has been observed to occur

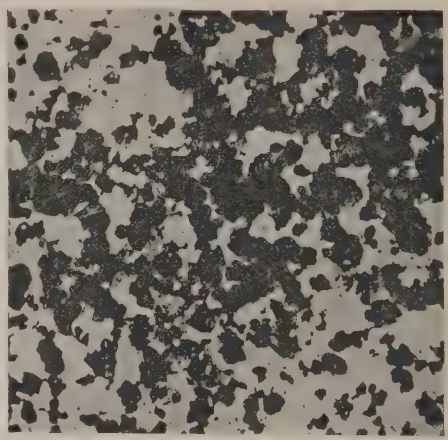

FIG. 16.—Martensite-troostite.

at as low a temperature as 350° C., while it occurs in all but very slightly deformed material at temperatures below the critical range. The size of the crystals which results from the annealing of deformed material is, however, the greater the less the amount of the deformation, and for low degrees of deformation large crystals are produced. In iron and low-carbon steels this fact must be taken into account, since poor mechanical properties, especially under suddenly applied stresses, accompany large ferrite crystals.

When these are likely to be formed it is better to carry out the annealing above the critical range, thereby ensuring a complete refining of the structure. Cases of extreme brittleness have been found in steel through the presence of coarse ferrite crystals produced in the manner indicated.

There is another effect produced in steels by annealing, which is of importance. At temperatures a little below the Ac1 point the cementite films of the constituent pearlite show a marked tendency to collect into rounded globules, embedded in a matrix of ferrite. This phenomenon is rendered more rapid by the previous cold-working of the steel, which appears to lead to the fracture of the cementite films, and so facilitates their rearrangement. This process has been called spheroidising by Howe. Pearlite which has undergone spheroidising is known as granular pearlite. It is obvious that this condition of the pearlite will not be accompanied by such good mechanical properties as pearlite, since the support offered to the ferrite by the cementite is not so effective. Steel in this condition is not very different in its mechanical properties from iron, and possesses a very low elastic limit. Advantage is taken of this fact in certain operations in which it is necessary to cold-work steel. In this spheroidised condition it is more easily cold-worked, and on that account annealing for the purpose of softening alone is often carried out below the critical point. Spheroidising treatment is often given to tool steel which has to be machined, since in this condition it is much softer than in the pearlitic state. *Fig.* 17 shows a piece of tool steel (containing 1·0 per cent carbon) after annealing at 650° C.

FIG. 17.—Globular Cementite and Ferrite.

§ (11) THE HARDENING AND TEMPERING OF STEEL.—Reference has already been made to the property which steel possesses of becoming very hard when quenched under suitable conditions. As has been indicated, hardening occurs through the rapid cooling of the constituent austenite, and it therefore follows that it is only when the steel consists entirely of austenite that it can be completely hardened. To secure complete hardening, therefore, the steel must be first heated to above its Ac3 point, and must be quenched before it falls below its Ar3 point. If it is quenched from within the critical range, only those parts will be hard which consisted at the moment of quenching of austenite. Experiments have shown that pure iron is not capable of being hardened by the severest quenchings to which it can be submitted. In fact, it is not possible in the pure metal to prevent the complete transformation of γ into α iron. The addition of quite small amounts of carbon confers the property of becoming hard on quenching: with 0·1 per cent the hardening is appreciable, but not large; as the amount of carbon is increased the "hardening power" increases, and becomes a maximum at a concentration near that of the eutectoid.

With hyper-eutectoid steels there is a tendency for some austenite to be retained in the steel after quenching, under which conditions the maximum hardness is not obtained. This, however, seldom happens if the quenching temperature exceeds but slightly the eutectoid transformation point, since under these conditions the excess cementite in the steel is not dissolved in the austenite, and hardening is then confined to a constituent which does not appreciably differ in composition from the eutectoid itself.

In hardening steel, as in annealing steel, care should be taken to avoid the production of a coarse austenitic structure, which produces a coarse, weak martensite, while it is of special importance that uniformity of temperature should be secured before steel articles are quenched, since irregular temperatures produce irregular hardening and lead to cracking of the steel. In practice heating of small articles is frequently carried out in lead baths or salt baths (chlorides and nitrates of sodium, potassium, calcium, and barium) on account of the ease with which uniform temperatures can be obtained by this method, and also because oxidation of the steel is less likely to occur.

The rate of cooling should be as rapid as possible if the maximum hardness is required, and in this connection the nature of the quenching medium is of importance. Hardening is usually effected by dipping the articles in cold

water or in brine solutions. Recent research has shown that the cooling power of a quenching bath is, within limits, independent of its actual temperature and heat conductivity. Benedicks contends that it depends almost entirely on its latent heat of vaporisation. Its temperature should, however, be low enough to prevent the adherence of vapour bubbles to the metal. According to this view, methyl alcohol is a superior quenching medium to water, while saline solution is not superior. Le Chatelier believes that specific heat is the most important factor. According to Mathews, the rate of cooling in water remains quite constant up to a water temperature of 37° C.; but with brine solutions, not only is a quicker rate of quenching obtained, but the cooling power of the liquid remains unimpaired up to a temperature of 65° C. When the maximum hardness is not required in the finished product, quenching may sometimes be carried out in oil. This does not produce such severe "hardening stresses" in the material, since the rate of cooling is not very rapid.

It is evident that a large piece of steel cannot be cooled as rapidly by quenching as a small piece, and that, when a certain size of sample is reached, the rate of cooling which can be obtained is not sufficient to secure hardening of the material. Unfortunately, in the case of simple iron-carbon alloys, this size is not large; in the case of a pure alloy, *i.e.* one containing practically no elements besides iron and carbon, it is very difficult to obtain a sample which consists entirely of martensite if the thickness is as much as half an inch. Commercial steels, containing the normal amounts of impurity, can be hardened in larger pieces, depending on the amount of impurity present; it will be shown in the section devoted to special steels that the addition of certain elements makes the hardening of large pieces much simpler.

In low-carbon steels, martensite, while considerably harder and stronger than the normalised steel, is still somewhat ductile. When, however, the carbon content exceeds about 0·3 per cent, martensite is extremely hard and brittle, and has practically no ductility. It is in fact practically incapable of withstanding any plastic deformation. Moreover, in addition to being extremely hard, the metal is usually in a state of considerable internal stress, and is liable to fracture very readily; indeed, hardened articles quite frequently crack spontaneously some time after they have been hardened, as a result of the existence of such internal stress. In order to reduce these stresses and to decrease its brittleness, hardened steel is usually "tempered" by heating to a relatively low temperature. This operation can be carried out without appreciably reducing the hardness, provided the temperature does not exceed a certain point. The tempering temperature varies with the use to which the articles are to be put. It has quite an appreciable effect on the stability of the material at 100° C., while reduction of brittleness is appreciable at about 200° C. At 300° C. the hardness is appreciably reduced, so that the tempering of tools is usually carried out between 200° and 300° C. Hardened steel objects subjected to tempering in air, if quite bright to begin with, gradually become coloured through the formation of thin films of oxide on their surfaces. The colours of these films vary with the temperature, and practical steel-workers gauge the amount of tempering by the colour of the film, the use of pyrometers for this operation being far from general. According to Howe, the temper colours and the corresponding temperatures are as follows:

Pale yellow	220° C.
Straw	230° C.
Golden yellow	243° C.
Brown	255° C.
Brown dappled with purple	265° C.
Purple	277° C.
Bright blue	288° C.
Pale blue	297° C.
Dark blue	316° C.

It is probable that the effect of time of heating is appreciable, and there is probably not a close relation between the colour and the temperature of heating. The temper colours, however, appear to be closely related to the *amount* of tempering, and the convenience of the method of colour observation in practice is so great that it is not likely to be discarded except in very special cases.

If the temperature is raised above 300° C., softening of the steel begins to take place rapidly. Up to this temperature the steel remains essentially martensitic in character. When this temperature is exceeded the martensitic character gradually disappears, and at 400° C. the structure consists wholly of troostite. In this condition the steel can no longer be regarded as "hard," since it possesses appreciable ductility. The structure is quite unresolved under the highest powers of the microscope, and etches to a uniform dark colour. Further heating results in the gradual production of sorbite, which is still not resolvable under the microscope, but is more ductile than troostite and etches more slowly. The difference between the constituents sorbite and troostite in tempered steels is not clearly marked, and it is difficult to say at what point the transformation of

one into the other becomes complete. When a temperature of 600° C. is reached it is possible to distinguish two constituents under high powers of the microscope, and in this condition the metal consists essentially of ferrite and cementite. The structure is, however, extremely fine, even after long periods of annealing. A photograph of a steel containing 1 per cent of carbon, hardened and reheated to 600° C., is shown in *Fig.* 18. The structure of such a steel is accompanied by most of the properties of a material which is required to withstand severe alternating stresses; it possesses high strength and elastic limit, with good ductility (toughness) and a high resistance to wear, shock, and fatigue. In consequence, a double treatment, consisting in quenching from above the critical range, followed by reheating to a temperature a little below Ar1, is frequently given to articles in which these qualities are desired. It should be noted here that for this purpose it is not essential that great hardness should ever be attained in the metal, and quenching in oil is generally sufficient to preserve a fine structure in the material. By subsequent reheating of this fine-grained metal the properties required in the steel can be obtained.

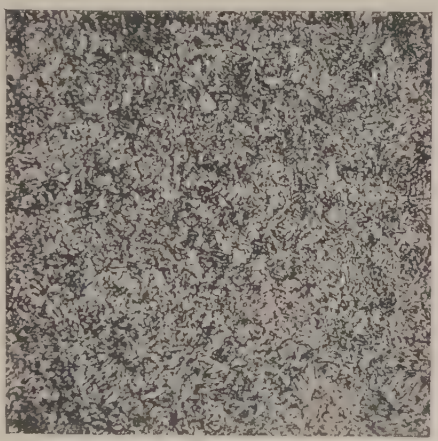

FIG. 18. Tool Steel.
Hardened and reheated to 600° C.

The rate of cooling after tempering appears to have little influence on the properties of steel (except certain special steels), provided it is not sufficiently rapid and irregular to leave severe internal stresses in the material.

§ (12) THEORIES OF THE HARDENING OF STEEL.—The great degree of hardness attainable by the treatment of a relatively soft metal such as annealed steel has never been adequately explained, though many and varied are the theories which have been advanced to account for it.

The discovery of the allotropy of iron by Osmond [1] led to the first "allotropic theory," which stated that steel owed its hardness to the retention of the iron in the form in which it existed at the quenching temperature—that is, above the A3 point. According to this theory the hard constituent was γ iron (known at that time as β iron), and the effect of carbon was merely to make the retention of γ iron more easy. γ iron was considered to be very hard at ordinary temperatures. At a later date, however, it was proved that γ iron is actually a somewhat soft material, even at ordinary temperatures; but, with the further investigation of the critical points, the possible effect of what we now know as β iron had to be taken into account. Osmond, Roberts-Austen,[2] and others were converted to the view that iron between A3 and A2 existed in a separate allotropic form, and this led to another "allotropic theory" still, known as the "beta theory," which attributed the hardness of steel to the presence of β iron. About the same time Metcalf and Langley [3] advocated another theory which took no account of the allotropic forms of iron, but attributed the hardening to the enforced solution of carbon in iron by rapid cooling, the hardness being a direct function of the rapidity of cooling. Hardening is accompanied by great internal stresses, from which result molecular strains, and hardening is produced by a similar process to the cold-working of metal. Carbon alters the molecular grouping, and the resulting strained structure is brought about within certain temperature limits.

For many years the controversy raged round these two theories, but little conclusive evidence was produced in favour of either. With regard to the beta theory, it has never been shown that β iron can exist in quenched steel; and if it had, there is but slight evidence to indicate that it would be hard. Rosenhain and Humfrey [4] have investigated the strength of the different varieties of iron at high temperatures, and have shown that, within the critical range, a slight increase in strength occurs when the A2 point is passed on heating. There is, however, little to indicate that beta iron would have any considerable hardness at ordinary temperatures. There is, also, strong evidence in the equilibrium diagram itself that β iron cannot exist in steels containing more than about 0·4 per cent of

[1] Osmond, *Iron and Steel Inst. J.*, 1890, No. I.

[2] Roberts-Austen, *Inst. Mech. Eng. Proc.*, 1893, p. 543.

[3] Metcalf and Langley, *Amer. Soc. Civil Eng. Trans.*, xxvii. 382.

[4] Rosenhain and Humfrey, *Iron and Steel Inst. J.*, 1913, No. I.

carbon, since this form of iron does not enter into the constitution of steels containing more than this percentage of carbon when they are slowly cooled, and there is no reason to suppose that it does so, even as a transition product, when they are rapidly cooled by quenching. The fact that hardening occurs in alloys containing more than 0·4 per cent carbon would appear to prove that the variety of iron existing between A2 and A3, whatever its properties, can have no influence on the phenomenon of hardening. Le Chatelier and Guillet have advanced the view that on rapid cooling through the critical range the transformation of the iron from the γ to the α state is not prevented, but that the steel remains, nevertheless, in the condition of a solid solution. Hardened steel is supposed to be a solid solution of carbon or iron carbide in α iron, owing its hardness solely to its state of solution. This view is based on the author's belief that β iron does not exist.

Arnold contends that eutectoid steel, above its eutectoid point, exists as the carbide $Fe_{24}C$, a chemical compound containing about 0·9 per cent carbon. This carbide, which he calls hardenite, is very hard, and, being retained by rapid cooling, imparts hardness to the quenched steel. In hypo- and hyper-eutectoid steels ferrite and cementite respectively are considered to be dissolved in hardenite. It follows that austenite and martensite [1] correspond to two different conditions of the same carbide $Fe_{24}C$. This theory is wholly speculative, and is not supported by a single experimental fact. It is, moreover, not compatible with the accepted constitutional diagram, and its author has not presented any diagram in which $Fe_{24}C$ can exist as a phase.

Within recent years a number of "stress theories" have been advanced. Stresses may be due to (1) the shrinkage of the outer shell on the interior during quenching, (2) the transformation with increased volume of γ into β or α iron. The existence of these stresses has been held to account satisfactorily for the hardness of quenched steel. Carpenter and Edwards [2] argue that in quenching steel these internal stresses cause internal straining of the metal, which in turn causes the formation of numerous mechanical twins and layers of amorphous material. The markings of martensite, in their opinion, correspond to these twins, and martensite is simply deformed austenite. This theory differs only in detail from some of the earlier theories, but it does offer, as none of the others did, an explanation of the structure of martensite. No theory which has yet been published offers a perfectly satisfactory explanation of the *structure* of this constituent.

McCance [3] believes that on cooling steel quickly from above its critical range the whole of the carbon remains in solution while the bulk of the iron is converted into the α variety. This α iron, however, is in an "interstrained" condition owing to the fact that its crystalline units have been denied the time to assume a homogeneous orientation, and the hardness of quenched steel is due to this interstrained condition. It is further contended that interstrained iron cannot be described as amorphous, since it could not then be magnetic.

Humfrey [4] considers that the hardness of steel is due to the presence of amorphous material. He says "the hard structure which can be produced in carbon steels by quenching, and in alloy steels by normal cooling, is due to the presence of a hard amorphous solution of α iron and iron carbide, which solution may be compared to Beilby's amorphous phase formed by overstrain." To explain the formation of this amorphous phase the author advances a theory that the passage of a substance from one allotropic modification to another of a different crystalline form involves the temporary formation of an amorphous state, corresponding to the liquid phase of the modification about to be formed. In steels such a change occurs at A3; and if, owing to the sudden cooling or to the presence of certain alloyed elements, the change point is lowered to a temperature below that at which crystallisation in the viscous mass becomes difficult, then the amorphous form will be retained in a metastable state in the cold.

Rosenhain [5] has suggested that the hardness is due to fineness of structure. In this condition the amorphous phase, which he considers exists between the crystals of all metals, would be present in a relatively large quantity, compared with the amount of crystalline material, and greater hardness would therefore result. He considers that the allotropic transformation takes place to a limited extent, and that the α iron and iron carbide have no time to form crystals of appreciable size.

Grenet [6] had previously advanced a theory somewhat similar to this, but had not specifically attributed the hardness to the existence of this amorphous metal. He states that the hardening produced by quenching is not due to the suppression of an inversion but to the lowering of the temperature at which it occurs to such an extent that it occurs with extreme

[1] Westgren (*Journal of Iron and Steel Institute*, 1923, No. 1) has shown, by X-ray analysis, that the iron in martensite consists mainly of α iron.

[2] Carpenter and Edwards, *Iron and Steel Inst. J.*, 1914, No. I.

[3] McCance, *ibid.*

[4] Humfrey, *Faraday Soc. Trans.*, 1914.

[5] Rosenhain, *Introduction to Physical Metallurgy* (Constable).

[6] Grenet, *Iron and Steel Inst. J.*, 1911, No. II.

rapidity. He says "we are thus led to the conclusion that hardness produced by quenching is due solely to the fineness of the structure."

§ (13) Cementation and Case-hardening. (i.) *The Process.*—The affinity of solid iron for carbon is so great that if it be heated in contact with a suitable carbonaceous material at a suitable temperature it readily absorbs this element. The purpose of cementation is usually to obtain a product having a soft-iron or mild-steel interior, with a high-carbon exterior which is capable of being hardened. An article can therefore be obtained, by suitable treatment, of which the outer skin, known as the "case," is hard, while the interior, known as the "core," is quite soft. Such articles, while they are able to withstand wear, are less liable to become fractured than articles which are hard throughout. The process has considerable practical application, and is widely used in the manufacture of machine parts subject to wear, armour plate, etc.

A great variety of carburising materials are used for this process; they may be either solid, liquid, or gaseous, though solid "cements" are most commonly used. The most important are charcoal (both wood and bone), charred leather, crushed bone, horn, mixtures of varying quantities of barium carbonate with charcoal and charred leather, and of salt and charcoal; liquid "cements" are used for obtaining an intense superficial hardening, and usually consist of potassium ferro-cyanide and potassium bichromate, used in the molten condition. The carburising of iron may also be carried out, under proper conditions, by means of gaseous reagents, such as illuminating gas or oil gases rich in carbon monoxide. Giolitti has shown that the presence of carbon monoxide is of importance during the process of cementation by means of solid cements, and it is probable that the greater part of the cementation is due to the generation of this gas.

(ii.) *The Absorbed Carbon.*—The quantity of carbon absorbed during cementation depends on (*a*) the composition of the iron or steel, (*b*) the carburising temperature, (*c*) the length of time at that temperature, (*d*) the nature of the carburising material.

(*a*) *Composition of the Iron or Steel.*—It is probably true that the smaller the amount of carbon in the steel the more rapid is the rate of absorption. As carburisation proceeds—that is, as the steel becomes richer in carbon—the greater is the time required for the absorption of a given amount. In cementation, the material used contains as a rule about 0·1 per cent of carbon. It should not contain more than about 0·2, since the production of a really soft core is rendered more difficult with higher concentrations. The presence of impurities and intentionally added elements may either facilitate carburisation or hinder it. Guillet states that those elements which form double carbides with iron, such as manganese, tungsten, chromium, and molybdenum, favour the absorption of carbon, while those elements which form solid solutions, such as nickel, silicon, and phosphorus, make it more difficult.

(*b*) *Carburising Temperature.*—While it is known that iron below its critical range will absorb some carbon, this absorption is very slow on account of the limited solubility of *a* iron for carbon. In order to attain a reasonably rapid rate of absorption the temperature must exceed the upper critical point, under which conditions the iron carbide formed is removed from the outside of the article by diffusion. The usual temperature is about 900° C., though in some cases much higher temperatures are used. It is, however, now recognised that the best results are obtained by the use of a temperature not appreciably higher than the upper limit of the critical range of the material which is being carburised.

(iii.) *Distribution of the Carbon.*—In most operations the production of an outer layer rich in carbon appears to take place relatively rapidly. The concentration of carbon in the outer layer depends on the carburising temperature. If the temperature used is 900° C. the maximum carbon concentration obtained in the outer layers is about 1·2 per cent. The concentration decreases from the outside inwards until the original material is reached.

(iv.) *Heat Treatment of Case-hardened Articles.*—It is generally required that articles which have been case-hardened should possess a hard skin, and to obtain this result they must be quenched from above the critical point of the case. This could be done by removing the articles direct from the carburising mixture and quenching in water. The structure of the material has, however, been rendered very coarse by the prolonged heating at the carburising temperature, and in order to obtain an article of good quality it is necessary to submit it to a refining treatment. Since, however, the carbon contents of case and core are very different, the refining temperatures are different. A double process is therefore adopted. The objects, after cooling from the carburising operation either slowly or through quenching, are reheated to about 900° C., which is above the refining temperature of the core, and cooled quickly, generally by quenching. This refines the coarse structure of the core. At the same time it secures the complete solution of the whole of the cementite in the case, provided the carburising tempera-

ture has not exceeded 900° C. The case, however, has been heated considerably above its hardening temperature during this treatment, and has become unduly coarse in consequence. The article is therefore reheated to a temperature slightly above the lower critical point of the steel and quenched. This treatment produces a case of maximum hardness and minimum grain size. It, moreover, reduces the hardness conferred on the core by the refining treatment to which it has been subjected, by causing the precipitation of free ferrite, which is not reabsorbed at the final hardening temperature. The case may be still further improved, in some cases, by slight tempering.

§ (14) Impurities in Steel.—Commercial grades of steel always contain, in addition to carbon, varying amounts of impurity, consisting chiefly of silicon, sulphur, phosphorus, and manganese, together with smaller amounts of other elements. Gaseous impurities, chiefly hydrogen, nitrogen, and carbon monoxide, are also usually present, and may, in certain cases, exert an appreciable influence. Silicon and manganese should, perhaps, not be termed impurities, since they are added to the molten metal for specific purposes, chiefly to secure sound castings; but their effect may be considered together with that of substances such as sulphur and phosphorus, which are present because they are derived from the raw materials, and it is not commercially practicable to remove them entirely.

Steel, as can be seen from a study of its equilibrium diagram, solidifies over a range of temperature, and the portions which separate first from the liquid metal are purer than those which separate later. A steel casting, like any other casting, has a cored structure, and the coring can only be removed by annealing after the metal is solid, and the rapidity with which coring can be removed depends on the rate of diffusion of the dissolved substances. Now, it so happens that the rate of diffusion of iron carbide in austenite is extremely rapid, so that, in the time taken for large steel ingots to cool down, it becomes distributed fairly uniformly through the solid steel. This is, however, not correct of all the other elements in steel, especially of the phosphorus, and with suitable etching reagents the coring of steel castings can readily be revealed. Heyn, Rosenhain and Haughton, Stead, and others have introduced reagents which are suitable for this purpose. These all contain small concentrations of a copper salt, and are known as cupric reagents. Up to the present we have only considered the structure of steel as revealed by the distribution of carbon. The cupric reagents produce a pattern, usually much coarser than that due to carbon, which is governed by the distribution of the dissolved impurities. By its use, therefore, it is possible to study the manner in which the cored structure of steel becomes modified as a result of the various treatments to which steel articles are subjected. Perhaps the most striking fact revealed by the cupric reagents is that, in the ordinary manufacturing processes to which steel is submitted, which involve heating for considerable periods to very high temperatures, uniformity of distribution of the dissolved impurities is practically never obtained, and the cored structure of the original casting can be revealed. During the rolling, forging, and other deforming operations to which steel articles are subjected, the structure of the casting is distorted in a great

Fig. 19.—Section of Steel Forging (Crank-shaft), etched with Cupric Reagent.

variety of ways; etching with a cupric reagent enables one to follow the actual manner of distortion of the original crystals in a remarkably clear way. *Fig.* 19 shows the structure of a crank-shaft, as etched with this reagent, the actual structure being magnified to about twice its natural size. The dark etching portions represent the purest portions, and the light etching parts the portions richest in dissolved impurity. They indicate very clearly the character of the deformation which has been put on the metal at different parts of the article. The structure of this article, when etched with other reagents, is found to consist of ferrite and pearlite of such small size as to be completely unresolved under the magnification here used. This method of showing the "cast" structure of steel has found considerable application in investigating the

failure of steel, and will be discussed in greater detail later.

Silicon exists in solid solution in steel as the compound FeSi (some writers give the compound the formula $FeSi_2$). It is not, as a rule, present in greater quantity than 0·3 per cent (0·9 per cent of the compound), while it is usually less than this amount. In these quantities it is without appreciable effect on the properties of the metal. Its distribution is not known.

Phosphorus exists as the phosphide Fe_3P, and exists in solid solution. It has a marked influence on the properties of steel, and is usually present in very small amounts. In very few cases does it exceed 0·1 per cent of the steel. It increases the hardness and brittleness of steel to a marked extent if present in greater quantity. Phosphorus is probably responsible, in a large measure, for the heterogeneity of steel which is shown by cupric reagents, though le Chatelier thinks that this effect is produced chiefly by oxygen, probably as iron oxide.

Sulphur is not present in a greater amount than 0·06 per cent in steel of satisfactory quality, in which case it usually exists in combination with manganese, with which it forms a compound MnS. If the amount of manganese is very low, and the sulphur content high, it exists as FeS. Manganese sulphide has a high melting-point, and probably solidifies before the steel itself is completely solid; it appears in steel castings as rounded particles, of a dove-grey colour, which have little influence on its properties. During the working of steel they become elongated and, if present in sufficient quantity, may be injurious. Iron sulphide shows a tendency to form continuous membranes or envelopes round the grains of austenite; it probably forms a eutectic with austenite, having a low melting-point, and appears to be the last constituent to solidify. The well-known brittleness of sulphur-rich steel at a high temperature is due to the weak mechanical properties, low melting-point, and manner of distribution of this constituent. In well-made steel it never exists in this form, since sufficient manganese is always added to prevent its formation. It has a yellow or pale brown colour under the microscope. The distribution of sulphur in steel is detected by taking "sulphur prints"; in this operation a piece of photographic printing-paper is soaked in dilute sulphuric acid and placed in contact with a polished surface. The presence of sulphur is revealed by the discoloration of the paper by the sulphuretted hydrogen liberated. The distribution of sulphur in steel can be studied in this manner.

It has been seen that manganese exists in steel partly in combination with sulphur. It may also occur, to some extent, as a silicate. As a rule, however, these do not account for all the manganese present. The remainder appears to form a carbide with some of the carbon present, this carbide being associated with the cementite, from which it cannot be distinguished by metallographic means. Manganese and iron can also form solid solutions with one another, and it is probable that in some cases, as for example when the carbon content is very low, manganese exists partly in this form.

In addition to the constituents already mentioned, a number of oxides and silicates are also sometimes found, chiefly as mechanical enclosures. Iron oxide itself is probably soluble to some extent in iron and steel, but only to a very slight extent.

IV. Cast Iron

§ (15) Iron-carbon alloys containing less than about 2·0 per cent carbon almost always follow the equilibrium diagram iron-cementite. When, however, the percentage of carbon exceeds this amount, under certain conditions dissociation of the cementite takes place, and graphite is found in the solid alloy.

The manner of solidification of cast iron is not very clear. By chilling alloys at a sufficiently rapid rate, the formation of free graphite can be entirely suppressed and a structure consisting of cementite and austenite (which later undergoes transformation) obtained. With slower rates of cooling graphite is formed, the amount being dependent partly on the composition of the alloy, especially with regard to certain impurities, and partly on the rate of cooling through and immediately below the solidification point. The mechanism of the formation of graphite has been the subject of much controversy. The suggested equilibrium diagrams of the iron-carbon alloys mostly indicate that under equilibrium conditions graphite can separate direct from the molten metal, both as a primary crystallisation and as a graphite-austenite eutectic. Recent experiments by a number of investigators point strongly to the fact that the formation of graphite is always preceded by the separation of cementite, which afterwards dissociates. This dissociation appears to be possible at the eutectic temperature, and proceeds more or less rapidly as the alloy cools to the transformation range of the austenite. Decomposition of the solid solution here takes place, and the eutectoid ferrite-cementite is formed. The cementite of this eutectoid may either persist or decompose, according to the composition of the alloy and the thermal conditions during cooling.

The micro-structure of cast iron varies with the state of the carbon. When the carbon is

all in the combined state, *i.e.* as cementite, the structure is that of a simple eutectiferous alloy, in which either austenite or cementite exists as a primary separation, according to

FIG. 20.—Cementite-pearlite (White Cast Iron).

the composition of the alloy. The microstructure of such an alloy is shown in *Fig.* 20. The white portions are cementite and the dark portions are pearlite, derived from austenite. *Fig.* 21 shows the structure of a cast iron in which some decomposition of the cementite has taken place; it contains

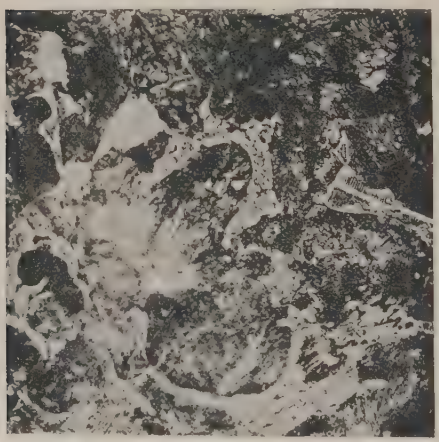

FIG. 21.—Cast Iron (Graphite and Pearlite).

practically no free cementite (other than that contained in the pearlite), but dark plates of graphite have been formed. *Fig.* 22 shows a cast iron containing almost all the carbon as graphite, in the form of curved plates; a small amount of pearlite is, however, present.

Cast iron in the "as cast" state is invariably a brittle material, possessing practically no ductility. In the alloys in which the carbon is all present as cementite this is due to the brittle character of this constituent. Where

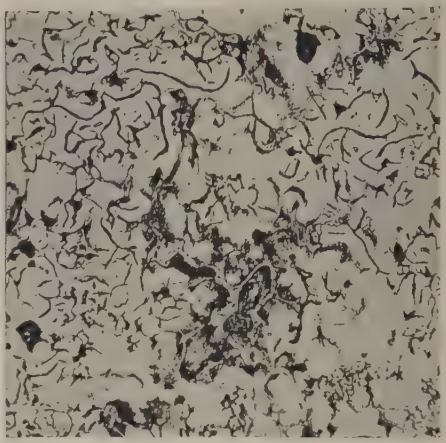

FIG. 22.—Cast Iron (Graphite, Ferrite, and a little Pearlite).

graphite exists, the plate-like particles destroy the continuity of the more ductile ferrite or pearlite, and fracture occurs through this constituent. The grey appearance of the fracture in this case has led to the use of the term "grey cast iron" to describe cast iron

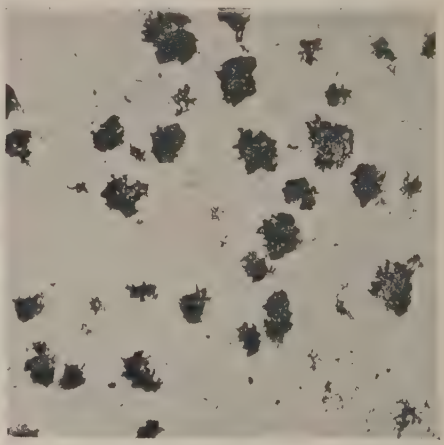

FIG. 23.—Malleable Cast Iron.

containing graphite; when graphite is not present the alloy is known as "white cast iron."

The conversion of carbon from the combined state to the free state is controlled, not only by the rate of cooling, but by the impurities present, and of these silicon has the most

profound influence. Its action is somewhat complicated, but the general effect of increase in silicon is to reduce the stability of iron carbide, and hence to favour the production of graphitic carbon. Sulphur, on the other hand, tends to make iron carbide more stable.

The conversion of combined carbon into graphitic carbon finds commercial application in the production of "malleable castings." Under certain conditions of heat treatment the graphite can be either (1) oxidised and removed from the metal, or (2) precipitated in a form in which it does not produce great brittleness. In practice this is usually accomplished by heating white-iron castings, packed in an oxidising material such as crushed iron oxide, and, as a rule, both the effects mentioned above are obtained. The annealing temperature varies slightly, but is usually about 800° C. The structure of a malleable casting produced according to one of these processes is shown in *Fig.* 23. The carbon in this case (known as temper carbon) exists in the form of rounded nodules, and does not completely interrupt the continuity of the ferrite. Such castings have considerable ductility, and are widely used.

D. H.

IRON-MANGANESE ALLOYS. See "Alloy Systems, Typical," § (16).

IRON-NICKEL ALLOYS. See "Alloy Systems, Typical," § (15).

IRON ORE, furnaces for reduction of. See "Furnaces, Electric," § (4) (i.).

— K —

KILNS FOR FIRECLAY ARTICLES. See "Refractories," § (18).

KRYPTOL: carefully graded powdered graphite mixed with some material (usually a form of carbon) having a high specific resistance; used for the construction of granular resistance furnaces.

— L —

LAGGING: a popular name for thermal insulating material. See "Furnaces for Laboratory Use," § (1).

LEAD BRASS. See "Alloys, Some Special," § (1) (iii.).

LEAD-TIN ALLOYS. See "Alloy Systems, Typical," § (9).

LEAD-TIN-BISMUTH ALLOYS. See "Alloy Systems, Typical," § (17).

LIGHT ALLOYS, advantages of. See "Aluminium Alloys," § (4).

Effect of temperature on strength. See *ibid.* § (3).

LIQUIDUS, in equilibrium diagram. See "Alloys, Constitution of," § (1) (v.).

— M —

MAGNESIA, PURE, TUBES AND CRUCIBLES. These can be made in the laboratory without great difficulty. See "Furnaces for Laboratory Use," § (3) (*c*).

MAGNESIA AND MAGNESITE BRICKS. See "Refractories," §§ (47), (48).

MAGNET STEELS used for making permanent magnets—tungsten, chromium, and latterly cobalt, being the metals usually added. The correct heat treatment is essential. See "Steels, Special," § (49).

MAGNETIC PROPERTIES of steels. See "Steels, Special," § (9); see also "Magnetic Measurements," Vol. I.

Use in investigating constitution of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (8).

MALLEABLISING: the rendering of cast iron soft and malleable by packing in iron oxide and exposing to heat. See "Metals, Thermal and Mechanical Treatment of," § (12).

MANGANESE in steel. See "Steels, Special," § (37).

MANGANESE BRONZE. See "Alloys, Some Special," § (1) (i.).

MANGANESE STEEL

§ (1) INTRODUCTORY. — It is hardly possible in a short article like the present to narrate the important and interesting points in connection with the invention of this steel, or to describe its many applications and various advantages. While many steels in common

use contain a small proportion of manganese, the name of manganese steel is particularly used in connection with an alloy steel containing about 13 per cent of manganese, with 1 per cent to 1·5 per cent of carbon.

Steel of this composition, discovered in 1882 as the result of the author's researches in his laboratories in Sheffield, has many remarkable and useful properties, and is in many respects quite different in character from other steels: in fact, its behaviour, specially as regards the results of heat treatment, is often quite the reverse of that experienced with other steels. For example, it is practically non-magnetic, and when quenched, instead of being hardened and made comparatively brittle, as is the case with carbon steel, its toughness is greatly increased.

Beyond one or two special products, including the Mushet self-hardening steel—a comparatively brittle product and only useful for tools—manganese steel represented on a large scale the first application for industrial purposes of steel containing high percentages—from about 10 to 15 per cent—of an element other than iron. It may be said with full justification that the present-day use of alloy steels is largely due to the attention called to their possibilities by the discovery of this interesting material. In this respect, therefore, it may not be out of place to quote here the opinion of the late Professor F. Osmond, who in his time was one of the leading scientists and metallurgists in France. He stated:

> The Hadfield discovery and invention of manganese steel was not only the discovery of a new alloy, curious, of great scientific value, and yet useful, but in the history of the metallurgy of iron it ranked as a discovery equal in importance to that of the effect of quenching carbon steel, and was the only one of the same order which it had been reserved for our age to make.

Professor H. M. Howe, the eminent American metallurgist, stated that:

> Manganese steel has a combination of properties which, so far as I know, was not possessed by any other known substance when this remarkable alloy was discovered by Hadfield. His further and extremely important papers with regard to this material have very greatly increased our knowledge of this remarkable substance.

§ (2) Physical Properties. (i.) *Tensile Strength.*—When suitably heat-treated, manganese steel has a high tensile strength—60 to 70 tons per square inch—combined with a ductility represented by an elongation of 50 to as high as 70 per cent measured on an effective length of eight inches, exceeding in this respect that attainable with the purest iron. A feature of its behaviour in the tensile test is the small local constriction at the point of fracture, the contraction of the cross-sectional area being distributed fairly evenly over the whole parallel portion of the test piece under stress. Its elastic limit is low and not clearly defined, that is, permanent sets are obtained with small tonnages, but for many purposes this has not been found to militate against its employment. Although its hardness of about 200 under the Brinell test is not high, it is specially resistant to wear, the peculiar reasons for which are stated later. A further feature is that it is practically non-magnetic, a fact which at the time the material was discovered seemed specially to attract the many scientists and engineers who examined it; that is, at the same time having in mind the large proportion of iron present, 88 to 90 per cent. Subsequent research has brought to light other non-magnetic alloys of iron, but none of the same peculiar nature as that possessed by manganese steel. In any case, it was the first malleable non-magnetic and ferrous product to be discovered.

These various physical qualities make manganese steel suitable for many purposes, for which it has outstanding advantages as compared with other steels, and it has in consequence had an important influence on engineering design, that is, the placing of a new material in the hands of the engineer.

(ii.) *Resistance to Wear.*—Its wear-resisting qualities render it suitable for a large range of applications, such as, for example, the jaws of stone- and ore-crushers, pins, buckets, and links for dredgers, tramway and railway points and crossings and rails, also hundreds of other purposes.

As one typical of many instances of the great advantages to be gained by the use of manganese steel in this direction, the important layout supplied in connection with the extensive system of the Sheffield Corporation Tramways may be quoted.

This is situated in Fitzalan Square, the centre of the city, from which the tracks radiate in all directions. The system is so arranged to provide a through service of cars, and, owing to the location of this special layout, practically the whole of the cars pass over it.

The information given below is of special interest, as it shows how economy in upkeep can be effected and how to minimise the delay caused by dislocation of traffic during reconstruction, this being a most important consideration in all industrial centres.

It is quite obvious that the frequent replacing of rails at this important part of the city was out of the question—in fact, impracticable; that is to say, the roads could not be closed to traffic.

In the early days of electric traction in the city this junction was constructed throughout with rails, points, and crossings of ordinary steel, but owing to the incline of the layout the amount of wear was so abnormal that the rolled carbon steel rails and other parts had to be renewed every few weeks, whereas after several years' service the amount of wear on the manganese steel construction was scarcely appreci-

able. Thus, it is quite correct to say that, without this special material, the through service could not have been maintained except with the greatest difficulty and abnormal expense.

The first junction layout in manganese steel supplied for Fitzalan Square was in 1901. Its condition was carefully recorded up to the date of removal in September 1907, when it was replaced, not because it was worn out, as it was admittedly fit for several years' further service, but had to be removed to meet the demands of the greatly increased car service and the necessity to redesign the junction so as to provide for additional tracks.

The second manganese steel layout was laid in September 1907, and has recently been re-laid without interference with the car service or general traffic.

The following data respecting the two layouts demonstrate the supreme wearing qualities of this most valuable manganese steel:

	First Layout. Laid Sept. 1901. Replaced Sept. 1907.	Second Layout. Laid Sept. 1907. Replaced May 1919.
Average number of cars per day	2,700	3,510
Tonnage per day	27,000	30,000
Maximum vertical tread wear per 10,000	·0021 in.	·0028 in.
Total vertical tread wear in six years	·484 in.	·781 in.
Total number of cars that passed over the junction	5,225,000	13,500,000
Number of points	8	16
Number of crossings	18	28
Number of intersections	28	40
Number of rails	47	59
Number of years' wear	6	12
Total weight of layout	20 tons	33 tons

It is estimated that this second layout, which was kept in service for the long period of twelve years, had a life of about forty-eight times that of the carbon steel layout previously in use, which was down only three months. As each layout costs about £2100, it will be seen how very considerable is the monetary saving effected.

(iii.) *Tenacity.*—The high tenacity and ductility of manganese steel, illustrated by *Fig.* 1, in which the effect of shots on a body shield is shown, accounts for its excellent behaviour as material for soldiers' helmets, body shields, and thin armour, applications which proved of such great service during the War, saving the lives and avoiding severe wounds of tens of thousands of British soldiers—in fact, Belgian, American, and other soldiers. It was also to have been adopted by the French Army had hostilities continued. Something like 6,000,000 of these helmets were made, and practical firing tests with shrapnel bullets demonstrated clearly the great superiority of manganese steel over other materials for this purpose; the physical qualities already mentioned, that is, high tenacity combined with extraordinary elongation, enable the material to resist the bullet by bulging without perforation—that is, the material takes up the impact in a remarkably efficient manner by

FIG. 1.—Helmet and Body Shield made of Manganese Steel.

indenting gradually and thus offering a larger surface of resistance.

The non-magnetic qualities of manganese steel have also been made use of by employing it for armoured and other structures near the magnetic compass on ships and aeroplanes. Such structures have no influence on the compass, and do not interfere with the directive action of the earth's magnetic field.

Other physical data are:

Electrical resistance, 71 microhms per c.c., or 7 times that of pure iron.

Thermal conductivity (0° to 100° C.) ·027 c.g.s. units, or about one-sixth that of pure iron.

Thermal expansion (0° to 100° C.) 18

millionths per ° C.—about 50 per cent more than that of pure iron.

Manganese steel behaves well in the casting operation, its fluidity and ability to fill moulds of intricate shapes being in some respects similar to that of cast iron. The castings are specially free from blowholes. The casting contraction of manganese steel is rather higher than that of ordinary steels, and amounts to ·30 to ·33 inches per foot.

Owing to its characteristic qualities, manganese steel cannot be commercially machined. This difficulty has been largely surmounted by so arranging the castings or forgings that they can be put into use without any tooling, or they are ground where this operation can be carried out. In the case of links, wheels, pulleys, gearing, etc., arrangements are made for casting into the articles mild steel bushes or liners, which can be machined in the usual manner.

Whilst manganese steel is difficult to roll or forge—that is, except in plain, simple forms—with experience and careful attention to temperature and manipulation rendered possible by improved methods of control, articles of uniform section, such as rails, sheets, and plates, are now successfully manufactured. Wire may be drawn, but in this respect the practical difficulties are considerable and restrict the field of use.

Fig. 2.—Photomicrograph of Manganese Steel as cast.

From the scientific point of view, manganese steel has proved of the greatest interest, and has led to much speculation in the formulation of theories of the behaviour of the alloys of iron. It has in some ways helped us to understand many of the problems met with; in others it has rather increased our difficulties in obtaining a correct explanation.

§ (3) Thermal Properties. — Quenching, preferably in water from high temperatures, which with most steels has the effect of producing intense hardness, has the contrary effect on manganese steel, and confers on it its condition of greatest ductility and toughness. It is chiefly in this condition that it is used commercially.

Another peculiarity of manganese steel is the entire absence of any critical point in its heating or cooling curves, except under the special conditions mentioned later. In all ordinary, as well as hardening and self-hardening, steels, these critical points are of considerable importance in guiding heat treatment. The conditions, both as regards rate of heating and cooling and maximum temperature, may be varied within wide limits[1] without the appearance of any critical points or changes in the character of the heating and cooling curves. In all these treatments the material remained non-magnetic in the case of manganese steel. These curves are therefore apparently of no value in guiding heat treatment. Thus the cooling of a piece of manganese steel as represented by the curve is very much of the same nature as that noticed when a specimen of a higher-carbon steel is quenched and cooled suddenly. In view of the extraordinary effect of heat treatment and quenching on manganese steel, it is specially curious to find there is no internal evidence—that is, as furnished by the usual heating and cooling curves—as to what is taking place internally in the crystalline or atomic structures during either heating or cooling; in other words, no clue is obtained with regard to the extraordinary change of structure which goes on in this material when it is transformed from the original embrittled state into that condition in which it possesses ductility not equalled by any other alloy of iron or steel.

As regards its structure when cooled, the microscope shows that manganese steel after being water-toughened has a pure austenitic structure, the carbon being in complete solution. *Fig.* 2 shows manganese steel in its original condition—that is, as cast; and *Fig.* 3 the same material water-quenched and toughened.

"Annealing" in the neighbourhood of 500° C. for many hours renders manganese steel quite hard, namely, about 450 to 500 under the Brinell test—and machinable, though not easily,—also very brittle, in contra-distinction to most other steels, where annealing has the opposite effect. Whilst the specific magnetism of manganese steel before undergoing this particular heat treatment is practically nil, about one part in 30,000, it reaches a value of about half that of pure iron after this heat treatment, its non-magnetic character being broken down. Even to-day there is no entirely satisfactory explanation

[1] Hadfield, "Heating and Cooling Curves of Manganese Steel," *Iron and Steel Institute Journal*, 1913.

of this extraordinary range in magnetic quality.

§ (4) Micro-structure.—Microscopical and chemical examination has shown the effect of the treatment producing a magnetic and brittle product just mentioned to be the deposition of a double carbide of iron and manganese in acicular form. This double carbide, which is much harder than the matrix, and stands out in relief on polishing a section of the material, is the prime cause of the hardening effect in the annealed product.

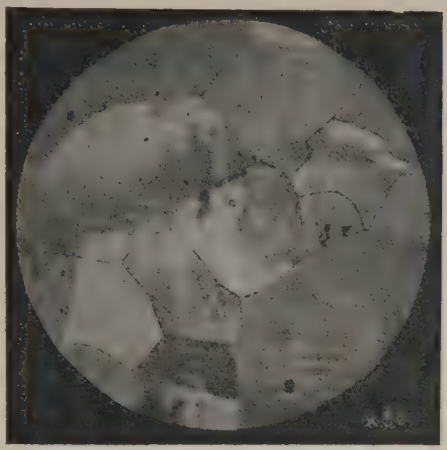

Fig. 3.—Photomicrograph of toughened forged Manganese Steel heated and water-quenched.

Reheating to a high temperature and quenching in water completely restores the ductility, non-magnetic qualities, and physical character generally of the material. An examination of the heating curve in this operation shows a critical point at 670° C. where the double carbide is re-dissolved, analogous to the critical point Ac_1 in carbon steel produced by the solution of the pearlite.

At the lowest attainable temperatures, even down to that of liquid hydrogen (− 250° C. or 23° absolute), manganese steel retains its non-magnetic qualities, but its ductility at this extremely low temperature, like that of many other steels, is practically destroyed, the tenacity at the same time showing a slight increase. Singular to say, however, this latter change is not permanent, as on restoring the material to ordinary temperatures it regains its original and extraordinary toughness. In view of the unusually high ductility of the material at ordinary temperatures, namely 50 per cent to 70 per cent elongation, on test bars of 8″ effective length, this is very remarkable (*Fig.* 4). Observations of the material under the microscope do not appear to show any structural changes at the lower temperatures.

The extraordinary toughness and ductility of manganese steel is shown by the stress-strain diagrams obtained by Professor A. W. B. (now Sir Alexander) Kennedy, then of the Engineering Department, University College, London, in connection with the discussion on the paper "Some Newly-discovered Properties of Iron and Manganese" read before the Institution of Civil Engineers, 1888. As Sir Alexander Kennedy then remarked, "the results given by the specimens are most remarkable as shown by the figures of work done under fracture. For ordinary bar iron this quantity is 4- or 5-inch tons per cubic inch, soft steel 6-inch tons, and only *very exceptionally* 7-, 8-, or 9-inch tons for very ductile bar steel of strong nature. But figures approaching 18-, 20-, and 24-inch tons per cubic inch as given by the specimens of manganese

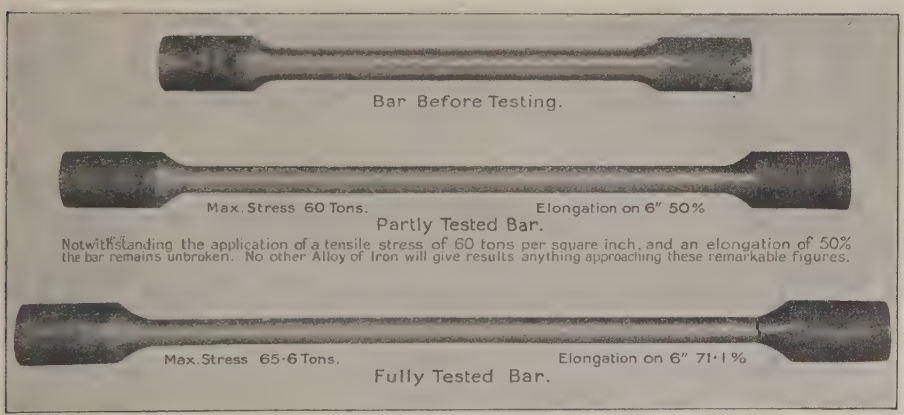
Bar Before Testing.
Max. Stress 60 Tons.
Elongation on 6″ 50%
Partly Tested Bar.
Notwithstanding the application of a tensile stress of 60 tons per square inch, and an elongation of 50% the bar remains unbroken. No other Alloy of Iron will give results anything approaching these remarkable figures.
Max. Stress 65·6 Tons.
Elongation on 6″ 71·1%
Fully Tested Bar.

Fig. 4.—Test Bars of the Hadfield Manganese Steel.

steel are, so far as I know, quite unprecedented. Certainly they are very remarkable."

In the same laboratory and on April 1, 1920, that is thirty-four years later, Professor E. G. Coker, F.R.S., tested a bar of the toughened manganese steel, which showed 66 tons maximum stress with 51 per cent elongation on a length of 8″. These results were plotted and are shown in the accompanying diagram, *Fig.* 5.

This test is of special interest, because the figures shown give the complete data in a very minute manner from start to finish of the test in question.

§ (5) HARDNESS.—A further and again remarkable characteristic of this material is its property of acquiring considerable hardness under mechanical deformation; in fact, this is the secret of its wonderful durability—a point for a long time not understood. The discoverer of this explanation was Osmond, who was particularly fascinated with the many curious properties of the material, and with whom the writer of this article for many years carried out important collaborative experiments. In its undeformed state the material is really rather soft, but when mechanically deformed it may acquire a hardness up to as much as 550 or 580 Brinell. It is this peculiar quality of hardening very considerably by pressure and deformation — no matter how slight — combined with the toughness of the material, which accounts for its very high resistance to wear; the working surfaces of the articles in use by slight deformation acquire this hardness and in consequence resist abrasion.[1]

Manganese steel shows its best wear-resisting qualities under the hardest working conditions, and where its durability has not been so great, that is when dealing with sharp, easily friable materials, this is probably accounted for by the fact that these do not sufficiently harden the working surfaces of the steel. The industrial value of a material, which the harder it is worked the better and greater its resistance to wear, will be readily understood.

Its hardness in the lathe is also due to the same cause. Deformation is produced by the cutting action and pressure of the tool which in its turn brings about the increase of hardness which is so valuable. When this hardness is produced then the material cannot be machined in a practical way.

The characteristic of manganese steel in the tensile test, referred to above and illustrated in *Fig.* 4, and the practical uniformity of section over the whole length even up to the point of fracture, may be explained on similar lines. In the course of the test a point is arrived at, as with other steels, where the conditions of stress become unstable, leading to a local constriction. In the case of manganese steel, however, the slightest constriction locally hardens the material to such an extent that it at once becomes at that point equally as strong as at other portions of the bar where no such constriction has occurred. No portion of the bar is therefore weaker than another, and elongation of the material continues uniformly throughout the length until finally the hardening effect of deformation reaches a limit.

The same fact operates in the drawing of manganese steel wire — passage through the dies mechanically hardens the material to a much greater extent than with ordinary steel, necessitating reduction in easy stages, with water toughening after each draw to restore the ductility.

It is an interesting scientific fact that hardness acquired in this manner is not accompanied by any appreciable modification of the non-magnetic properties.

The great importance of this invention, an entirely British one, is evidenced by the employment which the manufacture of this material now gives to many thousands of workpeople, not only in this country but in America and elsewhere, and the savings effected by its use in the world's work, that is in time, labour, and expense, amount to very large sums yearly. A total of about half a million tons of manganese steel has already been produced and put into service.

The following remarks with regard to these researches were made by the author when entering up and recording them in his Experimental Notebook on September 7, 1882:

> I was led to make these experiments, having in view the production of a steel which should be hard and at the same time tough. The experiments have led to some very curious results, perhaps most momentous ones that may quite alter present metallurgical opinions as to alloys of iron.

These words were written forty years ago, and have indeed proved to be true.

The table of bibliographical references, Sections I. to III. (appended on pages 571-2), gives the history of this material, to which both the words "curious" and "fascinating" can without exaggeration be truly applied. This bibliography chiefly deals with information existing at the time of the invention of this material. With the exception of the further papers of the author since that date there has been little outside information added to our knowledge of this subject of manganese steel. In fact, beyond gaining general experience in the manufacture of this material, manganese steel stands to-day practically of the same quality and type as when invented forty years ago.

R. A. H.

[1] This quality is fully described and discussed by the writer of this article in his memorandum on hardness in the report of the Hardness Test Research Committee of the Institution of Mechanical Engineers (Nov.-Dec. 1916).

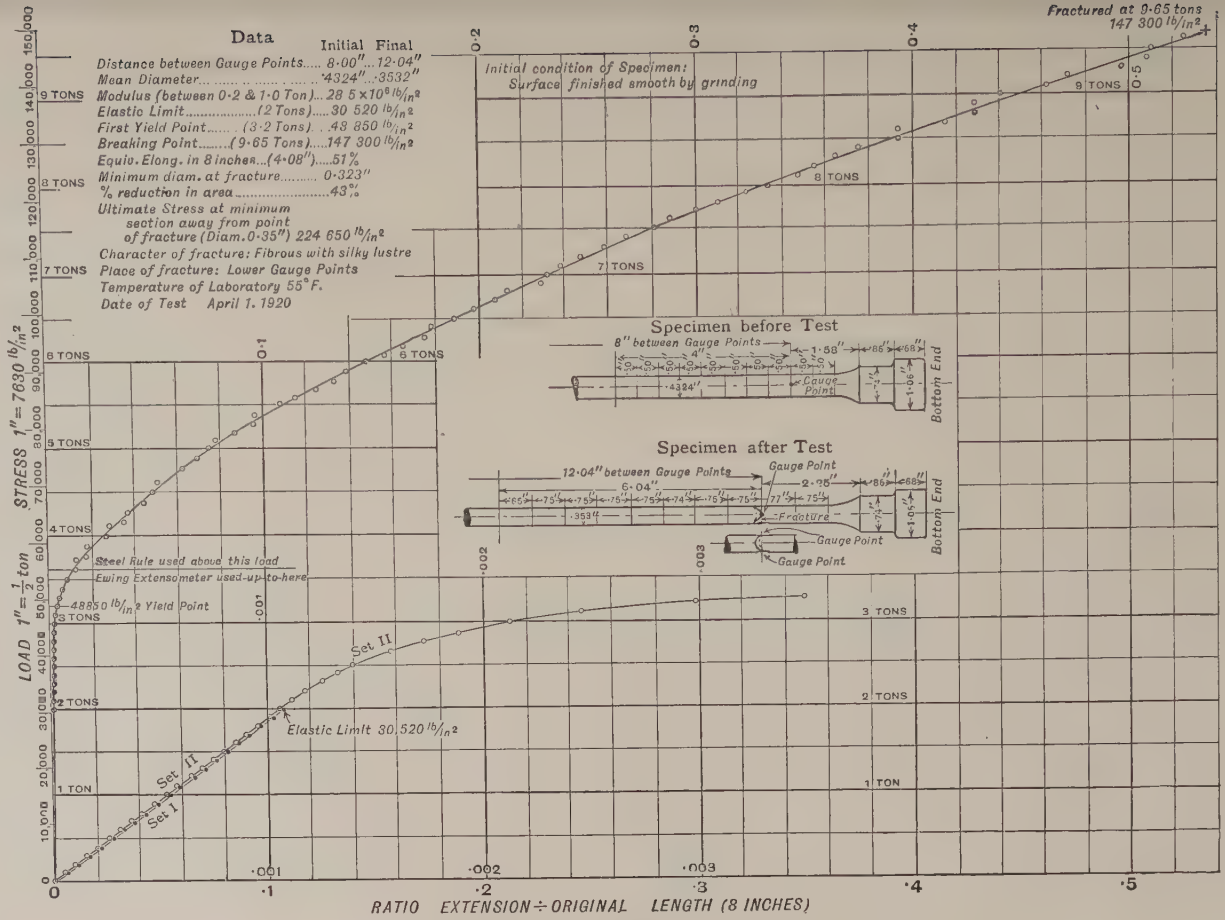

FIG. 5.—Tensile Test of Manganese Steel carried out by Professor E. G. Coker.

MANGANESE STEELS, influence of low temperatures on physical properties of. See "Steels, Special," § (4)A (v.).

MARTENSITE: a constituent of steel. See "Metals and Alloys, Micro-structure of," § (7); "Iron-carbon Alloys," § (10).

MECHANICAL DEFORMATION, with regard to rearrangement of crystalline structure of metals. See "Metals and Alloys, Micro-structure of," § (5).

MECHANICAL PROPERTIES of typical steels. See "Steels, Special," § (3).

MECHANICAL TESTS ON STEEL. Conditions under which they are carried out. See "Steels, Special," § (54); see also "Elastic Constants," Vol. I.

METAL MICRO-SECTIONS, mounting and levelling. See "Metals, Microscopic Examination of," § (3).
Preparation of. See *ibid.* § (1).
Preservation of. See *ibid.* § (4).
Treatment of difficult shapes. See *ibid.* § (5).

METALLURGICAL FURNACES. See "Furnaces, Electric," § (4).

METALLURGICAL MICROSCOPE. See "Metals, Microscopic Examination of," § (6).
Greenhough type. See *ibid.* § (6).
Le Chatelier type. See *ibid.* § (6).
Rosenhain design. See *ibid.* § (6).

METALS, failure of. See "Metals, Defects and Failure of," § (7).

METALS, DEFECTS AND FAILURE OF

AN exact definition of the meaning of the word defect in connection with metals is somewhat difficult to define. A metal article may fail because it is of unsuitable composition, or, though it is of suitable composition, because it has been wrongly treated during manufacture, or because it has been improperly treated in service. For the purposes of this article it will be assumed that it is desired to produce a metal or alloy of definite composition, free from appreciable amounts of impurity, and to prepare it in such a manner that it shall have the best properties associated with that particular class of material. The manner in which its properties may be adversely affected during the different stages of manufacture will then be considered.

Defects may be considered as being due to unsuitable conditions in any of the following operations of manufacture:

(1) Melting, pouring, and solidification of the ingot in the mould (defects of the ingot).
(2) Hot working.
(3) Cold working.
(4) Heat treatment.

§ (1) DEFECTS OF THE INGOT.—Under this heading may be considered, among other things, all causes which produce a molten metal which, at the moment of pouring, is of a different composition from that which is intended.

(i.) *Incorrect Mixture.*—This may arise through the use of impure materials, or scrap of uncertain composition, and may give a material in which the desired properties cannot possibly be obtained.

(ii.) *Loss during Melting.*—This may occur through overheating, as, for example, in the case of brass, where zinc is readily lost by volatilisation. Too low a temperature may be injurious when melting together metals of widely different melting-points, when one may remain unmolten or be incompletely dissolved in the other.

(iii.) *Incomplete Mixing.*—When dealing with metals of different densities, mixing, as a rule, only becomes complete if the molten metals are stirred sufficiently, since the lighter metal tends to float on the heavier, and equalisation of composition by diffusion is slow.

(iv.) *Contamination from Furnace Materials, etc.*—When the alloy is melted in large quantities, as in the case of steel and a few non-ferrous metals, it is a common method to melt the metal on the hearth of the furnace. In the case of a furnace of the open-hearth type the metal comes into contact with the material of the furnace, with the fuel gases, and with the products of combustion. An ideal furnace material, as a rule, is without action on the molten metal at the working temperature. In certain special cases, however, reactions between the furnace lining and the melt are sought, as, for example, in the basic open-hearth process in steel manufacture, in which phosphorus is removed from the steel by combination with the basic lining. Non-ferrous metals are generally melted in crucibles, from which they may derive impurities; aluminium alloys can become contaminated with silicon from clay crucibles, though under ordinary conditions of melting this does not happen to a serious extent. If the metal be overheated, however, the reaction is more rapid. Similarly, alloys of this metal sometimes dissolve iron when this metal is used as the crucible material if a suitable protective coating is not used. Crucibles containing graphite and clay are widely used for metal melting. Alloys containing nickel may be contaminated with carbon from such crucibles. Nickel may be ruined by melting in contact with carbon; this element is readily dissolved by the molten metal, but is deposited during solidification as a eutectic of the two elements. *Fig.* 1 shows the micro-structure of a sample of

nickel contaminated in this manner; it resembles the structure of cast iron, and the plates of brittle graphite destroy the ductility of the metal.

Contamination by the fuel is a common source of defects in metals. Where solid fuels are used it should be possible to prevent contact between the fuel and the melt. Through carelessness, however, particles of coal or coke may enter the crucible, and may impart carbon, sulphur, or other impurities to the metal. Copper alloys are particularly liable to absorb sulphur in this manner. Both when solid or other forms of fuel are used impurities may be acquired without actual contact with the fuel itself, through the medium of the products of combustion. It is practically impossible to protect metal completely from these, since they may reach the metal through the porous material of the crucible itself. It is, however, an advantage to protect the metal by the use of covered crucibles, since the volume of gas which comes into direct contact with the melt is thereby considerably reduced. Contamination at this stage may consist in actual chemical combination between the metal and elements of the gases. Copper, for example, readily absorbs oxygen or sulphur from the furnace gases, under favourable conditions, with the production of oxide and sulphide, which exist as impurities in the solid product. On the other hand, the metal may merely dissolve gases from the furnace; the influence of dissolved gaseous impurities largely depends on their behaviour during the solidification of the metal, and will be considered later.

FIG. 1.—Nickel contaminated with Carbon.

Among the minor sources of defects may be mentioned stirring-rods, tongs, and other implements used in handling crucibles, and carbon electrodes in some processes of electric melting.

§ (2) POURING AND SOLIDIFICATION. — Defects produced by incorrect conditions during pouring and solidification may be considered under three main headings: (A) Piping, (B) Blowholes and allied defects, (C) Structural defects, (D) Mechanical defects, cracks, etc.

(A) PIPING.—These defects are the result of the phenomena which normally accompany solidification. Piping is caused by the diminution in volume which occurs in most metals and alloys from the moment pouring is commenced to that at which the metal is quite solid. As solidification proceeds from the walls of the mould, liquid metal flows outwards towards the solid crystals which have already separated. So long as this influx of liquid metal can take place the production of a sound casting is possible; when the supply fails internal cavities are produced in the ingot or casting. This is known as piping. It is the more likely to occur the larger the casting, and in the case of steel can only with the greatest difficulty be avoided. It is further more common with high melting-point alloys, since it is difficult in this case to prevent the formation of a solid "crust" over the top of the mould before the metal inside is completely solid. If this takes place any shrinkage of the metal during further solidification must result in the formation of a pipe. In sand-castings of variable section unsoundness is often found in the thicker parts, since the supply of fresh liquid is stopped by the prior solidification of the thin parts. This must be counteracted by the use of gates and risers of ample size, which should, for preference, be placed on the thicker sections. Piping does not necessarily take the form of a single central cavity; in small castings it is more frequently found that the liquid has "drawn away" from the already solid crystallites in certain parts of the casting, giving a local "porosity" of the article. An example of this is shown in *Fig.* 2 in the case of an aluminium alloy. It is the form of the isotherms in the mass of the metal, and their displacement during solidification, that determines the form and importance of the pipe. The piping will therefore be reduced by slowing

down solidification and modifying unequally the rate of cooling in different parts of the casting in such a way as to deform those isotherms, and in particular by maintaining the metal in the open part of the mould liquid for the longest time. The object aimed at is to produce a deformation of the isotherms compensating for the retreat of the metal. In the case of steel, ingots are usually of large size, and a pipe is almost always formed. Special methods are adopted to diminish and control the position of the pipe. The most usual methods are—

(i.) *Thermal Methods.*—(*a*) Controlling the pouring temperature. In general there is a best temperature for pouring. This may have to be varied with mould temperature and other conditions.

(*b*) Keeping the top of the ingot hotter than the rest. This may be done by using moulds having their greatest width at the top. The effect of the shape of the mould on the position of the pipe is indicated in *Fig.* 3. Slow pouring is sometimes adopted; by suitably adjusting the rate of pouring solidification is made to take place from the bottom upwards. Artificial heating of the top, by various means, is sometimes adopted, while in other cases the top portion of the mould is constructed of refractory non-conducting material.

(ii.) *Physical Methods.*—The contraction of the metal in the mould is compensated for by applying external pressure to the ingot, either by lateral compression, longitudinal compression, or both. This is applied when the outer parts of the ingot are solid, but the central portions are still liquid. By allowing to a certain extent the formation of blowholes the central cavity is naturally decreased.

(iii.) *Characteristics of the Pipe.*—According to the conditions above mentioned the pipe may be localised, or be long and narrow, or may penetrate deeply and be continued by a series of cavities in a chain. According to whether the gases of the atmosphere have penetrated or not, the sides of the pipe may be oxidised or metallic. The cavities may be filled more or less with slag and cinder. In the cavities are found in relief the dendrites of solidification, while in the parts adjoining the cavities the metal is porous owing to the retreat of the liquid between the dendrites first formed. Rolling or forging flattens the cavities, but usually does not weld up the sides; it also produces, by the deformation of the arborescent dendrites, a fibrous texture which can be seen on breaking the metal. Pipe is therefore distinguished by—

(*a*) A more or less central position.

(*b*) The presence of slag and other non-metallic impurities.

(*c*) Fibrous fracture, oxidised or not.

(*d*) Concentration of dissolved impurities (see under "Segregation").

FIG. 2.—Shrinkage Cavities at Surface of Aluminium Alloy Ingot.

(iv.) *Detection of the Pipe.*—The pipe only exceptionally appears at the surface of the finished piece. It may be found in bars or billets by examining a fracture with the aid of a lens (fibrous appearance); the fracture should preferably be made by notching the bar all round and breaking across. One can also examine a polished and etched cross-section (excessive slag and segregation). These methods may fail, however, if the pipe is discontinuous. It may then be necessary to grind down the piece from the outside surface until the defect is disclosed.

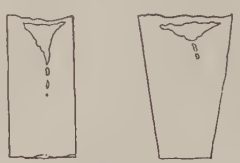

FIG. 3.

(v.) *Elimination of the Pipe.*—It is usual to remove the pipe by "cropping" the top portion of the ingot. The quantity of metal thus lost depends on how effective have been the methods adopted to reduce piping. Further, the destination of the ingot may be considered in determining the amount cut off; for example, for the manufacture of tubes or cannon the centre is removed, and less cropping may then be allowed. In certain cases the ingots may be

split longitudinally into four pieces, and these rolled into bars. The pipe is then brought to the surface.

(B) Blowholes. — These result from the imprisonment in the metal during solidification of bubbles of gas. Gas may arise from (*a*) a decrease, sudden or otherwise, in the solubility of dissolved gas during cooling in the mould and solidification; (*b*) reactions in the molten metal which give rise to gaseous products.

Gases dissolved in metals are taken up from the furnace atmosphere while the metal is molten. The treatment in the furnace is therefore important. While it is not necessarily true for all metals, it appears in some cases that heating to an unnecessarily high temperature is harmful in this respect. The casting conditions have an influence on both the amount of gas liberated and the position of the blowholes on the ingot. For each metal and alloy there appears to be a best temperature of pouring with which the liberation of gas is a minimum. This casting temperature may vary with the size of ingot, mould, temperature, etc. All the gas liberated by the cooling metal does not necessarily form blowholes; some will escape from the metal and some will be driven into the pipe. In castings cooled quietly bubbles tend to be formed on surfaces parallel to the walls of the mould, and to be elongated in the direction perpendicular to the walls. The zone of bubbles approaches nearer to the surface of the casting with metals of high melting-point, and when the casting temperature is high. The surface of a blowhole may be oxidised or not, according to whether the cavity was in contact with the air or not while the metal was hot.

All thermal processes tending to diminish piping also tend to prevent the formation of blowholes, since they also allow bubbles of gas to escape. The physical methods, involving compression of the ingot, have little influence on blowholes. In the case of iron and steel the evolution of gas can be to a large extent controlled by the addition of certain elements to the metal immediately before casting. Silicon and small amounts of aluminium are used. They prevent the formation of bubbles before the metal becomes solid. Similar methods have been little studied in non-ferrous metallurgy. In these alloys control of the casting temperature is the best remedy.

(i.) *Effect of Blowholes on the Working of Metals.*—Forging or rolling elongates these bubbles and brings the sides together, but does not, as a rule, weld them up. When the working is severe the blowholes are drawn out into long lines; on opening one of these "lines" the sides appear fibrous on account of the drawing out of the dendrites which existed on its surface. If the bubbles are near the surface they may open out during rolling or drawing, giving rise to spills on the surface; if this does not happen "blisters" may be formed on the surface during subsequent annealings by the expansion of the gases contained in them.

(ii.) *Detection of Blowholes.*—They do not appear on the surface of an ingot or casting, which may have a perfect skin while being honeycombed inside. They are readily detected on a polished section. On a cut or machined surface the larger holes only appear; the smaller holes are hidden by the "dragging" of the surface. In bars superficial lines can be revealed by cleaning up the metal, or by careful turning. If the bar is cut rapidly with oil on the surface, blowholes can sometimes be revealed by the release of bubbles of gas. During forging, if the surface of the metal is being extended in a direction perpendicular to the direction of the lines, they open up and become more visible.

(C) Structural Defects.—Under this heading may be considered defects due to (i.) undesirable structure or constitution, and (ii.) segregation.

(i.) *Structure and Constitution.* — Size of structure has an important effect on the properties of metals and alloys. In a casting, size of structure is governed largely by the rate of solidification; this in turn depends on the nature of the mould, on its temperature, and on the casting temperature of the alloy. Sand moulds are poor conductors of heat and lead to slow solidification, with the production of a coarse structure in the metal; metal moulds produce a finer structure. The higher the temperatures of the mould the less the difference between the temperatures of the mould and the metal, and the slower the process of solidification. A high casting temperature produces a coarser structure since it warms the mould before solidification commences. Similarly, the larger the casting the coarser the structure. For material of the highest quality a fine structure is desired, and, when possible, metal moulds should be used. When this is impossible, improvements may often be effected by the introduction of metal chills into sand moulds.

When solidification is rapid crystals tend to be elongated in a direction perpendicular to the walls of the mould. When two faces of the mould meet at a sharp angle, the growing crystals may assume a structural arrangement similar to that shown in *Fig.* 4 (*a*). A surface of weakness then exists at the junction of the two sets of crystals; by rounding off the corner of the mould as in *Fig.* 4 (*b*) an improved structure is obtained.

In some alloys, especially those which undergo

transformations in the solid state, the constitution may depend on the rate of cooling, either through the solidification point or through critical points at a lower temperature. As an example may be quoted the case of

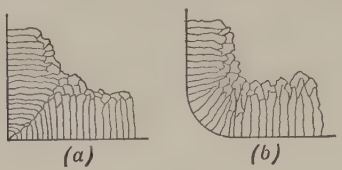

FIG. 4.

cast iron of certain compositions, which have an entirely different constitution according to whether they are cooled slowly or quickly (see section on "Iron-carbon Alloys"). Rapid rates of cooling give a " white iron " which is very hard and brittle; slow rates give a " grey iron " which is relatively soft.

(ii.) *Segregation.*—Defects due to segregation are extremely common in alloys. Solidification takes place over a range of temperature, and the solid crystals at any moment during solidification are in equilibrium with a liquid of different composition; it follows, therefore, that unless solidification is extremely slow the last portions which become solid have a different composition from those which separate first. In general, the impurities of an alloy become concentrated in the last portions to become solid, and their influence may depend more on the amount to which they segregate during solidification than on the total quantity present in the alloy.

Segregation of impurities generally occurs in the neighbourhood of the central cavity or pipe of a casting, since this is the last portion of the ingot to solidify; it must be remembered, however, that every crystal of the casting has, as a rule, a variable composition from centre to periphery, so that segregation is associated with every individual crystal of the alloy. The first kind of segregation, which consists of a general variation of composition of the alloy from outside to centre, is sometimes referred to as the " major segregation "; the variation in composition in the individual crystals themselves is known as " minor segregation." The major segregation in an alloy is the more likely to lead to defects, and it should be reduced as much as possible. Since, however, it is due to the natural process of solidification, it is impossible to avoid it completely. Perhaps the best method of reducing it is to use ingots or castings as small as possible for the required purpose. The problem is not really of serious importance except in the steel industry, in which the policy of using small ingots has become common.

Segregation may have a direct influence on the properties of an alloy on account of the inferior quality of the metal in the segregated zone, which will, in general, be more brittle and less resistant to shock than the purer portions. It may be further harmful in the case of alloys containing entangled oxides, slag, and similar material. Particles of such impurities are frequently suspended in liquid metal before it is cast; the larger particles rise to the surface or sink while the metal is still liquid in the crucible or ladle or mould, but smaller particles are trapped in the metal. These are pushed before the growing crystallites, and become collected in the last portions to solidify. They are therefore associated with the most impure portions of the casting, where their presence is probably most harmful. This arrangement of the particles is found particularly in the case of the slag particles of steel, which are always present to some extent even in the best metal. During forging and working of an alloy the segregated areas are elongated in the direction of working, and may be drawn out into lines or bands. Annealing will remove the effects of segregation by facilitating diffusion; during this process the crystals become uniform in composition, and soluble constituents pass into solution, and, unless they are present in sufficient quantity to saturate the solid solution, they may be removed in this manner. The amount of annealing necessary, however, is sometimes considerable, and is the greater the larger the original crystal structure and the lower the temperature of annealing. In some cases the amount of annealing required is so great as to be commercially impracticable. Slag particles and other impurities insoluble in the solid metal cannot be removed in this way, and retain their position in the alloy except in so far as this is modified by subsequent mechanical treatment to which the alloy may be submitted.

The detection of segregation (coring) requires, in many cases, the use of special etching reagents, and for many alloys suitable reagents have yet to be discovered. An etching reagent which will reveal the crystalline structure will not necessarily reveal small differences in chemical composition in neighbouring parts of the alloy. For example, ferric chloride is very commonly used for etching brass, for which it is, in most cases, very suitable. It does not, however, as a rule, reveal the segregation of the casting. Ammonia, on the other hand, is an excellent reagent for this purpose. Perhaps a more striking example is found in the case of steel; reagents have recently been developed for revealing the coring or minor segregation of steel, and their use has led to a considerable advance in our knowledge of the solidification of steel and its behaviour

during the various processes of manufacture. (The use of this reagent will be referred to later.)

Sulphur printing is also resorted to in the case of steel. In this process, a piece of ordinary photographic bromide paper, which has been soaked in 10 per cent sulphuric acid solution, is placed in contact with a ground surface of the metal. Particles of metallic sulphides in the metal react with the acid, producing sulphuretted hydrogen, which reacts with the silver salts in the paper and produces a dark stain. The distribution of the sulphur can thus be studied.

Ordinarily the result of segregation during solidification is to produce an ingot in which the outer layers near the mould surface are the purest. In certain cases, however, the reverse is found. For example, in the case of the silver-copper alloy used for coins (sterling silver) it is usually found that the concentration of copper in the outer layers is greater than in the centre of the ingot. The difference in concentration between outside and centre is greater in chill castings than in sand castings, and it has been suggested that the phenomenon is due to the existence of a temperature gradient in the molten metal before solidification commences. The exact mechanism is not understood. The phenomenon is sometimes known as "liquation." It has been observed in a number of alloys, and may be general if the conditions are suitable.

Segregation not infrequently occurs through differences in density between different constituents in an alloy. In this case, if the crystals which first separate are lighter than the liquid from which they are deposited, they will tend to rise to the top of the ingot. Difficulties from this cause are frequently met with in the case of certain bearing metals. For example, in tin rich bearing metals in which the compound SnSb occurs the lighter crystals of the compound rise rapidly in the mother liquor, and if solidification is slow very considerable differences in composition will be found between top and bottom of the casting. The remedy in such a case is to reduce the time of solidification.

(D) Mechanical Defects, Cracks, etc.—A large variety of mechanical defects may be found in an ingot, the seriousness of which depends in many cases on the use to which it is to be put. They may be classified under the following main headings: Cracks and fissures; distortion; and surface defects.

(i.) *Cracks and Fissures.*—Cooling of an ingot takes place from the superficial regions, which become colder than the centre. During the first period of cooling, therefore, while the contraction of the outside is greater than that of the interior, the outer layers are in tension, and under favourable conditions cracks will form. During the later stages of cooling, however, the conditions are reversed, and internal ruptures or "fissures" may be produced.

Cracks may form at any stage after solidification has commenced. They may be either longitudinal or transverse. Such cracks are exposed to the oxidising action of the atmosphere, and become coated with a layer of oxidised metal which, if not removed from the surface by chipping or scraping, will persist through the subsequent operations of working, and lead to a defect in the product. The production of transverse cracks is facilitated by sticking of the ingot or casting to the mould, either through welding or through roughness of the mould surface. In the case of castings of complicated shape made in metal moulds it is essential to remove the casting as soon as possible after solidification is complete, since the contraction of the cooling metal is prevented by the relatively cold mould. The same is true in the case of sand moulds when the sand cannot "give" sufficiently to follow the contraction of the casting. Sand cores for hollow castings have to be specially prepared with this point in view, and they are usually made in such a manner that, under the influence of the high temperature and contraction pressure of the casting, they collapse into powder.

The tendency to cracking in the peripheral zone is increased by a normal disposition of the peripheral dendrites to the side of the mould, and this effect is particularly marked at the angles of rectangular ingots, the diagonals being planes of weakness. The form which a crack takes depends mainly on the temperature at which it is formed. Most metals and alloys, when near the melting-point, fracture by the separation of the crystals from one another, whereas at low temperatures it is more usual for a crack to be produced by the fracture of the crystals themselves. Intercrystalline cracking near the melting-point sometimes takes place under very low stresses, and materials which are particularly liable to this form of failure require very careful treatment in the mould.

It by no means follows that severe contraction stresses will result in fracture; in some cases the metal will become plastically deformed, and thus relieve the stress.

Fissures are, in many respects, more serious defects than surface cracks, since they are invisible. They occur in the interior of the metal, and the zone of segregation is naturally most subject to these defects. If the internal fissure is produced while the centre is still at a high temperature the fracture is coarse-grained, and has a characteristic aspect; this occurs especially in very large ingots, such as steel ingots, in which the cooling

is lengthened to shorten the pipe. If the fissure occurs at a low temperature it is fine-grained; such fractures are found particularly in metals possessing a low elongation, especially when they also undergo a low temperature transformation, as in the case of self-hardening steels.

They may also be produced during reheating (see under "Heat Treatment").

(ii.) *Distortion*.—In certain cases, as has been indicated above, unequal rates of cooling, or obstructions in the mould, may cause distortion without producing rupture of the material. The seriousness of such a defect will depend on the purpose to which the casting is to be put. In the case of an ingot intended for forging or rolling it may not be serious, but in a shaped casting it may be sufficiently serious to render it unsuitable for its purpose.

(iii.) *Surface Defects*.—A large number of minor defects, denoted by a still larger number of names, mainly products of the foundry, may be found. Cold shots, cold shuts, or cold drops are defects produced by splashing of the metal in the mould; the drops become rapidly chilled on hitting the walls, and are not remelted by contact with the rising metal. They are then trapped, usually between the surface of the casting and the wall of the mould. Veins are irregular wavy markings which occur on the surface of a casting when too much "dressing" has been applied to the mould surface. Fins or feathers are produced when metal runs between the joints of the mould. Scabs are rough projections caused by the mould breaking or being washed away by the metal. Buckles or swells are produced by the mould being pushed out of shape by the molten metal. Incrustations of sand arise from the entanglement by the liquid metal of particles of sand which have become detached from the mould. Ripple markings and ridges in the skin of the casting are produced by irregular rising of the liquid metal on the sides of the mould.

Mechanical surface defects such as have been described are probably most serious in the case of ingots intended for forging and rolling. They give rise to a variety of surface blemishes in later operations. Even when they do not lead to cracking they are preserved as surface defects in the finished product. They become drawn out in the direction of rolling and forging, and are found as longitudinal defects in such products as rolled bars. They may, however, be removed to a greater or less extent by fettling or dressing with grinding wheels, chisels, etc. Cracks are a somewhat more serious defect. They are frequently too deep to be removed by chipping or grinding, and become drawn out into longitudinal defects. Their surfaces become oxidised both during cooling of the ingot and during reheating for forging or rolling, and give rise to rokes or seams. They may sometimes be removed by machining.

§ (3) Hot Working.—The hot working of metals may be carried out by a number of different methods, of which the most important are forging, rolling, and extruding.

Forging is a term applied to a large number of different kinds of working. It may consist of hammering, either by hand or by means of power hammers, or by pressing in hydraulic presses; in either case the metal may be worked into a suitable shape by the use of dies fastened to the anvil block and hammer. The defects in the material which arise at this stage of manufacture may be considered in three main groups:

(*a*) Defects due to an imperfect casting.

(*b*) Mechanical defects, due to unsuitable mechanical conditions.

(*c*) Defects due to unsuitable thermal conditions.

Some of the defects due to imperfect castings have already been indicated in considering the defects of the ingot. It is clear that any operation which deforms a casting will also deform the defects which it contains, and the manner of the deformation in any part controls the modification in the character of the defects in that part. In general, the defects alter their shape in the same manner as the casting itself. Thus slag inclusions are drawn out in the direction of elongation of the forging; the extent to which they are drawn out depends on their hardness relative to that of the metal itself at the forging temperature. A hard particle, for example, in a soft metal will not be drawn out to the same extent as the metal. Blowholes become closed up, though the opposite sides do not as a rule weld together, and they therefore become lines of weakness. Under severe conditions of working, casting defects frequently lead to the development of cracks in the metal, for which they form a starting-point. This is particularly the case in high-tensile alloys of most metals. With pure metals, which are as a rule fairly soft and easily forged, casting defects frequently do not lead to failure of the metal during forging. In alloys, when the metal is made stronger and the ductility consequently reduced by the addition of other elements, casting defects are much more likely to lead to failure of the material during forging.

A common defect in forgings and pressings is a fold, caused by one portion of the metal being turned over and pressed into the article. In such operations as the forging down of an ingot into a bar or long forging, this may arise through a careless application of the

hammer or press. In such operations as drop-forging or pressing into dies it may arise through faulty designing of the dies; for example, solid metal does not readily enter acute angles in the dies, and may bend over and form a fold. It is also important that there should be sufficient metal to fill the die and to form a small fin at the junction of the two portions of the die. Surface defects tend to become concentrated in this fin, which can be removed by machining.

If the best properties are required in the forging, as is the case when the articles are finished to shape in dies, it is important that sufficient work should be put on the metal to break up the original structure of the casting. The properties of metal which has been cast but not worked are, as a rule, very inferior to those of wrought material. One of the chief reasons for this is that a casting usually has a coarsely crystalline structure, with which is associated weak mechanical properties. By working such material to a sufficient extent under suitable conditions of temperature, recrystallisation takes place and a more desirable structure is obtained. When, however, the amount of work to which the metal is subjected is small, recrystallisation may not take place; if it does occur, it results in the formation of crystals which, while they may be smaller than those of the casting, are large when compared with those found in severely worked material. It is desirable, then, that the forging operations should be so arranged that all parts of the material, if possible, receive sufficient deformation to bring about an improvement in their mechanical properties. In the production of forgings of large size this point is frequently overlooked, and examples of large shafts have been met with in which the outer layers were completely refined during forging, while the centre possessed a coarse structure characteristic of a casting.

(i.) *Thermal Conditions during Forging.*—There is for all metals and industrial alloys a general tendency for the material to become softer as the temperature is raised, although in some cases the temperature-hardness relation is more complicated in the neighbourhood of transformation points in the metal. It may therefore be stated, as a general rule, that the higher the temperature of working, the less the power required to bring about a given amount of deformation. There is also, for most materials, a region of temperature where the ductility is a maximum. This is not necessarily the same as the region of greatest softness. This latter region is that which is most suitable for forging. If one works at a high temperature in the neighbourhood of the solidus the ductility tends to become nil, and fracture occurs between the grains, which at such a temperature have usually become very large. The low cohesion between the grains makes them come apart under very low stresses, and complete disintegration of the metal may occur. Even when this does not happen "burning" may take place, either as a result of incipient fusion, or of the penetration of oxidising gases between the boundaries of the crystals. Metal which has been "burnt" is usually very weak and brittle, and breaks with an intercrystalline fracture. The choice of a suitable working temperature is most important in the initial stages, when the casting is being broken down. After this has been accomplished the range of working temperature is usually considerably increased.

The influence of impurities on hot working is often very important. For example, the presence of excessive sulphur in steel is harmful from this point of view. On the other hand, additions may be made to some alloys solely with the object of improving the forging and rolling qualities; 1 per cent of silicon added to certain aluminium alloys, while having little effect on the mechanical properties, greatly facilitates the operations of working.

Rolling consists in deforming a metal by passing it through metal rolls. The size and shape of the rolls depends on the type of product and the character of the ingot or bar from which it is made. In the production of sheet and strip metal "flat rolls" of cylindrical shape are used. In the production of such forms as rod, rails, angle, girders, etc., the rolls are provided with grooves through which the metal is passed; at each pass a definite alteration in the shape of the article is brought about, until with the final pass the required shape of the finished article is obtained. The conditions of rolling are very different from those of forging; as a rule, the amount of deformation of the material is considerably greater, while at the same time it is much more uniform. As in the case of forgings, defects of the casting have their corresponding defects in the rolled product, being drawn out in the direction of extension of the metal. In the case of rolled bars defects become elongated in one direction only, and assume a rod-like form; in the case of flat plates or sheets, in the manufacture of which the ingot is usually extended in two directions at right angles to one another, defects take the form of flat plates parallel to the surface of the plate or sheet. The seriousness of such defects will depend on the use to which the material is put, and on the direction of the working stresses in relation to the lines of weakness caused by the defects.

Among the more common defects are rokes and laps. Rokes are formed from ingot cracks, blowholes at or near the surface, and

certain kinds of surface defect of the ingot, and in the case of rolled bar they are usually radial when examined on a cross-section. Laps are formed during the process of rolling when the surface of the ingot contains defects, such as scabs, fins, etc., which have not been removed by grinding or machining. They may also occur as a direct result of the rolling operation, when a fin is formed during passage through the rolls, and is afterwards folded over during a subsequent pass. They are also sometimes formed through the use of rolls with a defective surface; for example, in the manufacture of certain steel products the rolls are cooled periodically by the application of a stream of water. The effect of alternate heating and cooling is to cause small cracks in the surface of the rolls, which lead to slight ridges, or "roll marks," which, in the case of small sections, may become rolled over and form a lap.

Various types of defect are produced by unsuitable mechanical conditions during rolling. Defects in the surface of the rolls naturally produce defects in the product. Sometimes imperfect lubrication of the rolls causes the metal which is being rolled to stick or weld on to the roll, when, instead of coming out flat, it may become wrapped round it, or, although it may be stripped off as the metal emerges from the rolls, cracks and other surface defects may be formed. Cracking or breaking up of the metal may result from too severe work in any one pass. Care must be taken to prevent pieces of foreign matter, such as loose bits of metal, oxide, etc., falling on to the metal or the rolls, being carried through the rolls and pressed into the metal. Metals which oxidise rapidly must be brushed clean of any loose oxide before passage through the rolls. The mechanical adjustment of the rolls is also a matter of importance, especially in the rolling of sheet or strip. If the degree of reduction of section is not uniform in all parts, the product is warped. For example, if one edge of the sheet or strip is reduced in section more than another it becomes bent into a curve. If the centre is deformed more or less than the edges the sheet becomes buckled.

The remarks made with reference to the effect of thermal conditions on forging also apply to the operation of rolling, though in certain respects the conditions may be different. When material is to be used in the "as rolled" condition, it is essential to ensure that the final passes are carried out under conditions which will give a product of the required mechanical properties. These are largely dependent on the thermal conditions at the moment of finishing. The finishing temperature should, in general, be such that recrystallisation of the deformed material takes place, but should not be so high that a coarse structure is obtained. This is not easy to secure in some operations on thin sections, which tend to cool very rapidly in the rolls. In such cases it is desirable that the material should be reheated at a late stage in the rolling operations.

§ (4) Cold Working.—Cold working usually consists in (*a*) reducing the cross-sectional area by rolling, hammering, or drawing; (*b*) distorting the material by bending, flanging, cupping, or twisting; and (*c*) punching or shearing.

Cold working is usually employed for one or more of the following reasons: (*a*) the metal cannot be worked hot, either because it is not ductile at a high temperature, or on account of excessive scaling, etc.; (*b*) to obtain certain modifications of the mechanical properties associated with cold-worked metal; (*c*) to obtain a very smooth even surface; (*d*) to obtain extreme accuracy as to size; (*e*) to obtain certain products, such as wire and thin sheet-metal stampings, which could not conveniently or commercially be obtained by other methods.

Defects may arise from insufficient working, from excessive working, or from unequal working. Insufficient working may produce a material which does not possess suitable properties for the purpose for which it is intended. Many articles made from metal wire or sheet depend for their strength and stiffness on cold working of the material, and in many cases insufficient work on the material would give a product which would be much too weak or soft. High-tensile steel wire, such as is used in the manufacture of wire ropes, depends to some extent on cold work for its strength. Excessive cold work, on the other hand, renders metals very brittle, and for that reason must be avoided. Manufacturing defects are probably more commonly the result of too much cold work than of too little. In the cold rolling of sheet too much cold work leads to the development of cracks, particularly of edge cracks, and to splitting.

Probably the greatest number of defects is attributable to unequal working of different parts of a material. An article which has been worked unequally is in a state of internal stress, which may lead to failure in a variety of ways. Such a stress may be superimposed on the working stress of the article in service, and lead to fracture under a comparatively small externally applied stress; it may lead to "season cracking," by which is understood gradual failure without the application of any external stress (such failures sometimes occur years after an article has been made); it may cause cracking on annealing, owing to the different recrystallisation properties of the

differently worked parts. Defects due to unequal working are not uncommon in manufacturing operations. Sometimes the defects are in the interior of the article, and are not easily detected. Such defects occur in many drawing operations, especially on rods and wires of large diameter, in which the exterior parts are deformed to a much greater extent than the interior, and the stresses thus produced are sometimes sufficient to produce internal fracture of the article, which is then said to have "drawn hollow." Cold-shearing and cold-punching affect the metal to a varying depth from the sheared or punched edge, depending on the thickness of the piece and the nature of the metal. The distortion in such a case is non-uniform, and may lead to failure if the piece is bent across the sheared edge, or where there is a punch-hole. The danger from such causes is so great that in many structures, such as boilers, the use of punched rivet-holes and sheared edges is particularly excluded. The bad effects may be removed by machining off the embrittled portions, and in some cases by annealing.

The act of machining may, and frequently does, produce serious local deformation of an article. Machining is essentially the production of a local stress, by means of an edged tool, sufficiently great to shear the material. Although rupture may be confined within narrow limits, deformation may extend for a relatively great distance into the surrounding metal. This depth will depend on the depth of the cut, and on the shape of the tool. Frequently the deformation on a machined surface is so great that the material is found to contain a mass of small cracks which, in service, form a convenient starting-point for the development of larger cracks. With grinding wheels or emery paper the penetration of the hardening effect is smaller.

§ (5) Heat Treatment.—Heat treatment, in its most general sense, may be taken to mean the application of heat either to make the metal easier to work, by rendering it softer or more ductile, or to secure certain desired changes (beneficial or otherwise) in its constitution or physical properties without mechanical work. By common usage, however, the term has become restricted to the latter application, which will be dealt with under this subsection. The former application has been discussed under the subsection dealing with hot working.

Heat treatment may therefore be defined as "the change or series of changes in temperature, together with the rate or rates at which they take place, applied to a metal or alloy to secure certain desired conditions or properties."

The term heat treatment is frequently, though incorrectly, used in the restricted sense of quenching followed by tempering or reheating, as applied specially to steels.

The main factors which influence the result of heat treatment are—

(i.) The state of the material before treatment.

(ii.) The rate of heating.

(iii.) The temperature at which the treatment is carried out.

(iv.) The time of heating.

(v.) Contamination, volatilisation, etc., of the material while hot.

(vi.) The rate of cooling.

The above factors will be considered separately, after which reference will be made to a number of special methods used in the working and manufacture of metal articles.

(i.) *The Material.*—The effect of heat treatment will vary according to the mechanical and thermal treatment to which the metal has previously been submitted. The mechanical condition is, in some cases, of particular importance, since the degree of working in all pure metals, and in many alloys, largely controls the character of the recrystallisation which takes place. In a casting, for example, heat treatment produces recrystallisation only when the metal has been deformed, unless there are constitutional transformations of certain types. Undeformed castings of such metals or alloys as copper, alpha brass, and some alloys of aluminium, to name but a few examples, undergo no changes of crystal size on annealing at any temperature below the solidus, so that any defects due to coarse crystallisation of the casting cannot be removed by thermal treatment. After mechanical deformation, however, metals will recrystallise if the conditions are favourable. In general, the minimum recrystallising temperature is the higher, and the resulting crystal size the greater, the less the deformation to which the material has been submitted. A metal which has received a slight amount of cold work may develop, on recrystallising as a result of heat treatment, a coarse crystalline structure with poor mechanical properties, and it is therefore important to adjust either the severity of the working, or the temperature of annealing, so that such a result may be prevented. In certain operations, especially those in which a metal is deformed locally, defects due to this cause are particularly likely to occur. For example, in such operations as spinning, portions of the material are frequently deformed to an extent which favours excessive grain growth on annealing. Such articles may frequently be preserved in a good mechanical condition by annealing at a temperature too low to cause recrystallisation of the slightly deformed parts, but high enough to remove the cold work, and cause a beneficial recrystallisation, in the severely

worked parts. Defects of this kind have been found in cold-reeled brass bars, in the decarburised skin of cold-drawn steel tubing, and in the ferrite ghosts of steel boiler plate which has been bent cold.

(ii.) *The Rate of Heating.*—This must not be sufficiently great to produce great inequalities in temperature in different parts of the article. Cracks may be produced in brittle material through local differences in expansion; in cold-worked material this may be facilitated by the prior recrystallisation of some parts; in the case of hardened steel it may be facilitated by local tempering, with the production of severe local stresses.

(iii.) *The Temperature.*—The temperature at which a metal or alloy is heated is obviously of importance in any heat treatment, since it is by suitable regulation of temperature that the desired conditions or properties of the material are obtained. A very large proportion of the defects produced by faulty heat treatment result from the incorrect regulation of temperature, either through ignorance of the most suitable temperature conditions, or through careless manipulation, faulty furnaces, or defective pyrometers. It is impossible to give any complete summary of the defects which may arise from faulty regulation of temperature, since the field to be covered is so large; practically all metals and alloys, in the forms in which they are used commercially, may have their properties modified by heat treatment, and the effects of elevated temperature must be considered in every case in relation to the constitution of the alloy. A general indication of the manner in which incorrect heat treatment leads to the production of unsuitable material may, however, be given with reference to some of the common alloys.

It is obvious that, for practically all materials, the useful temperature range for heat treatment is limited by the solidus of the alloy; if this temperature is exceeded partial melting of the alloy takes place, and such melting may be accompanied by an undesirable segregation of alloying elements or impurities, since the liquid and solid phases in equilibrium with one another at any temperature are seldom of the same composition. Furthermore, on cooling, the properties of that portion which has been molten are similar to those of material in the "as cast" condition, and may therefore be considerably inferior to those of the parts which have not become molten. It may therefore be assumed that, in the case of worked material, or of castings which have previously been submitted to beneficial heat treatment, any further heat treatment which causes partial melting to occur is harmful. In any case, metal which is partly molten is in an extremely weak and fragile condition, and may break up or crack under its own weight, while the molten parts are always liable to run out, leaving cavities in the material. Notwithstanding the obvious danger of heating to a temperature as high as the solidus, defects from this cause are by no means unknown. In the case of steel which is heated to a high temperature for forging or welding, partial melting sometimes takes place; the crystal boundaries of the material, in which melting first commences, become weakened, and the steel is liable to break with a coarse intercrystalline fracture; such material is said to be "burnt" (see also under (iv.)). Certain non-ferrous alloys, notably alloys of aluminium, are submitted to a hardening treatment which consists in quenching them from a temperature as near to the solidus as is practicable, and unless the temperatures are carefully controlled the same type of defect may be produced. It may, in such a case, be detected by the typical appearance of the quenched liquid alloy when examined under the microscope.

Crystal growth in metals is greatly facilitated by exposure to high temperatures, and where the best mechanical properties are required it is usually necessary to avoid material with a large crystal size. The use of annealing temperatures near the solidus of the alloy is therefore to be avoided, since it facilitates the production of large crystals. For most of the commoner metals, such as iron and steel, copper alloys, and aluminium alloys, mechanical softness can be obtained by annealing at a temperature considerably lower than the solidus, and, unless some special change related to the constitution of the alloys at high temperatures is desired, no advantage is obtained by the use of a high annealing temperature. When special changes related to the constitution of the alloys are required, as in the case of the alloys of aluminium referred to above, defects must be avoided by careful regulation of the temperature and the time of heating. The use of high temperatures must also be considered in relation to possible contamination by furnace gases, etc. (see under (iv.)).

The use of too low a temperature may equally be harmful, in that it may be insufficiently high to bring about the desired changes; for example, in the case of cold-worked material, it may be insufficient to bring about adequate softening.

The use of correct temperatures is particularly important in certain cases where the results of heat treatment depend on the careful control of transformations at certain critical temperatures. This is specially applicable in the heat treatment of steel, a subject which can only be adequately dealt with in a lengthy treatise. The general effect of thermal treatment on steel has been considered in the article on "Iron-carbon Alloys," with particular

reference to the constitution of the alloys, and no further general consideration of this system need be made here; the subject would not, however, be complete without some reference to the defects which may arise in any metal through improper control in the neighbourhood of the temperatures at which constitutional changes occur. In many metals and alloys passage through a critical point, either on heating or on cooling, is accompanied by a change in the crystal structure; for example, in the cases of the metals iron, nickel, and zinc, passage through some or all of the allotropic change points is accompanied by a recrystallisation of the metal. The formation of a new set of crystals in such a case is somewhat similar to the process of solidification of a metal, in that recrystallisation takes place from a number of nuclei, which is controlled by the conditions of passage through the critical temperature. In general, the number of nuclei, and therefore the number of crystals in the product, will be the greater the more rapid the rate at which the change takes place. In alloys containing two or more constituents critical temperatures may occur in one or more of these constituents, and it may be desired to effect a change in one constituent while leaving the other unchanged. Such a case is found in the heat treatment of case-hardened steel articles, and serious defects frequently arise through inaccurate temperature control, which produces effects in one of the constituents which it is desirable to avoid.

Passage through a critical point is frequently used in order to obtain a fine structure from one which was originally coarse, and it is obvious that by a suitable arrangement of the conditions of heating and cooling this can be done. In a number of cases, however, the structure of the low temperature modification of the alloy is dependent on the structure of the high temperature modification at the moment at which passage through the critical point occurred on cooling. This is particularly the case when cooling through a critical point results in the decomposition of one phase into two, the relative arrangement of the two constituents being governed by the size of the crystals from which they are formed. As a rule a better structure is formed from fine than from coarse crystals; it is therefore, as a rule, desirable that a critical point should not be exceeded by a sufficient amount, or for a sufficient time, for a coarse structure to be obtained.

A critical point in an alloy which is accompanied by recrystallisation is of great value, quite apart from the fact that it allows of the variation of properties by varying the constitution. It frequently permits the correction and removal of a defective structure, which could not otherwise be removed except by complete remelting of the alloy. Consider, for example, the case of an alloy which had been so treated to develop a coarse arrangement of the constituents accompanied by unsuitable properties for a particular purpose. If such an alloy can be heated through a critical point above which those constituents disappear with the formation of a new constituent, then the original defective structure can be obliterated, and, by suitable regulation of the conditions of heating and cooling, the same constituents can be reproduced in a more useful form. This treatment is made use of with great frequency in the heat treatment of steel, which, provided it has not been burnt, can have its properties modified in a profound manner by suitable heating and cooling through the critical range. An alloy which has no critical points, such as brass, is frequently ruined beyond repair by an incorrect heat treatment in the final stages of manufacture; for example, a coarse overheated structure in such an alloy can only be removed by recrystallisation after further deformation, or by complete remelting.

(iv.) *The Time of Heating.*—The time during which an alloy is maintained at a temperature is of importance; it must be sufficiently long to allow the changes which are desired to take place. Some of these changes take place rapidly. Recrystallisation of cold-worked material is almost invariably a rapid process, and usually demands but a few minutes at a suitable temperature for its completion; further heating merely gives opportunity for the crystal size to increase, while prolonged heating may develop too coarse a structure. For the annealing of cold-worked material it is unnecessary to expose an alloy to high temperatures for prolonged periods. In other cases, however, the desired changes may take place slowly at any annealing which is applicable; for example, in the heat treatment of castings it is sometimes desired to obtain a more uniform distribution of the alloying elements than exists in the material in the "as cast" condition. In large castings which possess a coarse structure, this may involve the diffusion of elements through relatively large distances in the solid metal. The process of diffusion in the solid state is usually very slow, and long periods of annealing may be required for it to become complete. In some cases annealing for two or three weeks at a temperature not far removed from the solidus has been found insufficient to complete the process. Such periods of heating are usually not required, but in many cases annealing for a large number of hours may be necessary to obtain a desired result. In any heat treatment which involves the solution of one constituent in another or the reaction of one constituent with another, the time required to complete

the change will depend on the size of the structure in the original piece, and should be adjusted with this in view. Any period of annealing less than a certain minimum will fail to bring about the desired object; any period in excess of the necessary amount merely affords opportunity for coarsening of the structure, oxidation, contamination, etc.

In any operation the time of heating should be sufficient for the required temperature to penetrate to all parts of the article. This is of importance in dealing with large masses of metal and in certain operations in which the articles to be heated are enclosed in "boxes," as for example in case hardening or in close annealing. In such cases the temperature of the outside may reach the desired point a considerable time (sometimes hours) before the centre. The measurement of the temperature of the articles under these circumstances is a matter of considerable difficulty, since pyrometers placed in the furnace near the objects give no reliable indication of the temperature of the interior parts. Whenever possible a pyrometer should be inserted into the article or annealing "box"; when this is impracticable, as is frequently the case, a "dummy" of the same size as the article may be placed in the furnace and the pyrometer inserted into holes suitably placed.

FIG. 5.—Burnt Tool Steel (hardened).

Inequalities in temperature during heat treatment are responsible for a large number of defects and failures in metal articles, especially in certain cases where the heat treatment consists in the regulation of temperature within small limits in the neighbourhood of critical points. In the hardening and tempering of steel it is of great importance to secure the attainment of the correct temperature within very narrow limits, but it is also necessary to obtain uniformity of temperature; much of the cracking of steel during hardening is due to the existence of inequalities of temperature at the moment of quenching.

(v.) *Contamination.*—Serious defects may arise from contamination of the material while it is hot. Reference has already been made to the burning of a metal through exposure to an excessive temperature. This may consist simply in incipient fusion of the material, which usually starts at the crystal boundaries. In other cases, however, the same name is applied to metal which has been oxidised in the crystal boundaries during exposure at a high temperature. In certain metals oxygen and other oxidising gases appear to be able to penetrate between the crystals under certain circumstances and produce a film of oxidised material which destroys the normal cohesion between the grains, and renders the metal weak and brittle; fracture naturally takes place by separation of the crystals from one another, and in many cases, though by no means invariably, the fracture has a dull oxidised appearance. Steel is particularly liable to this type of defect; *Fig.* 5 shows a photomicrograph of a steel tool which fractured in use and broke with a coarse-grained intercrystalline fracture. It will be seen that the crystals are extremely large, and that each is surrounded by a thin dark film of oxidised material. The coarse structure indicates an exposure to a very high temperature, which has been sufficient to "burn" the material. Cast iron is liable to "grow" if repeatedly heated to a high temperature; oxygen from the air penetrates along the plates of graphite which it contains, and oxidises the iron, with the formation in the interstices of the material of oxides of iron. The pressure of the growing oxides causes an expansion of the mass. In other cases reducing gases exert a harmful effect; copper may be seriously embrittled by the action of reducing gases if, as is usually the case, it contains any copper oxide. This constituent is reduced to copper, which, however, is porous and without appreciable mechanical strength. The gases appear to be able to penetrate through the solid copper when it is hot.

An interesting and somewhat unusual failure of a "manganese-bronze" article has recently been described.[1] The article in question, an end plate of a turbo-alternator rotor, was essentially a β brass containing small amounts of manganese and aluminium, and was subjected to very light stresses in service. Local heating had occurred during running, and molten solder had come into contact with the alloy; penetration of the solder had taken place for a considerable distance between the crystal grains, and had produced extreme local brittleness. Further experiments showed that this alloy was rendered brittle, and failed through intercrystalline penetration under very low stresses, by contact with molten alloys melting at as low a temperature as 70° C.

Oxidation of a metal does not necessarily take place by intercrystalline penetration of the oxidising gases; all steels are liable to become oxidised on the surface, at high temperatures, with the production of a decarburised skin; intercrystalline oxidation only occurs at temperatures near the solidus of the alloy. A decarburised surface is specially undesirable when a steel article must be hardened, since the decarburised layer will remain soft after the normal quenching operation. Such articles as tools, files, springs, gauges, case-hardened parts, etc., must be carefully protected from decarburisation during all the heating operations to which they are subjected.

In some alloys loss by volatilisation may be serious; brass, for example, may lose zinc from the outer layers through prolonged exposure to an excessive temperature.

(vi.) *Cooling.*—The rate of cooling should, whenever possible, be uniform throughout the whole of an article. Irregular cooling leads to irregular contraction, and may lead to deformation and warping of the article. In any case, it is liable to produce internal stresses, which may lead to failure under a stress less than the normal breaking stress of the material, or by season cracking. When critical points occur in the metal irregular cooling may cause partial or complete suppression of the transformations associated with these points locally in the article, with the accompanying conditions of internal stress. At the same time the properties of the material will vary from place to place. Rapid rates of cooling are sometimes adopted to bring about certain conditions in alloys; steel, duralumin, and similar aluminium alloys, and certain aluminium copper alloys, may be cited as examples. An insufficiently rapid rate of cooling will fail to bring about the improvement in properties which the treatment is designed to produce. In the hardening of steel the rates of cooling required are sometimes very great, and the most vigorous quenching methods must be adopted. Under such circumstances it is evident that there is a limit to the size of article which can be hardened. Irregular hardening of alloys such as those mentioned almost invariably leads to warping.

§ (6) Other Processes of Manufacture. —Some other processes of manufacture which do not conveniently come under the above headings may be considered.

(i.) *Welding.*—Welding is now such a common operation in the manufacture of metal articles that it requires some separate consideration. Welding may consist merely in heating the metal to a point below its solidus, and hammering the different parts together; such an operation is commonly carried out on iron (especially wrought iron) and on the precious metals. In the case of iron, defects may arise from the entanglement of oxide at the junction of the two surfaces which are being welded, since it is very difficult to heat this metal to the temperature necessary for welding without oxidising the surface; in some operations the iron is heated to a temperature sufficiently high to melt the coating of oxide formed, when the liquid oxide is forced out of the weld more easily. The same process is also used in the manufacture of steel articles, but the presence of carbon renders the metal more difficult to weld, and the process is never used for high-carbon steels; when used with steel it is usually found that the carbon content of the weld is very low, since the metal is decarburised on the surface by the preliminary heating, and during the welding operation by entangled oxide. An oxide inclusion in a weld is shown in *Fig.* 6 under a magnification of 150 diameters. Other defects may arise from heating the metal to too high a temperature (burning); if the temperature is too low, complete union may not be effected.

In recent years the term welding has been used to describe processes in which union is obtained by actual melting either of a substance which acts as a solder, or of a portion of one or both of the pieces which are to be united. Usually a flux is used to dissolve metallic oxides formed during the process. These welds suffer from the disadvantage that the properties of the weld itself are those associated with metal in the as cast condition: furthermore, the welding operation necessitates the heating of the neighbouring parts to an exceedingly high temperature, as a result of which coarse structures of weak mechanical properties may be formed. When possible, such welds should be refined by suitable heat treatment. Defects due to unsoundness of the weld itself, inclusions of oxide, etc., cannot be cured by such treatment.

(ii.) *Galvanising, Electroplating, Protective Coatings.*—Defects in these operations may

[1] Dickenson, *Inst. of Metals J.*, 1920.

arise through improper preparation of the surface which it is desired to coat (oxidised, dirty, or greasy surface), through the use of unsuitable electrolytes and current densities (in electroplating), through the use of impure alloys and incorrect temperatures (in galvanising, tinning, etc.), and through the occlusion of gas by the base; the latter phenomenon may arise in the case of the electro-galvanising or plating when, under certain conditions which are not well understood, brittleness occurs which is ascribed to the occlusion of hydrogen; brittleness of springs has been ascribed to this cause. Fracture of the coating by any means usually leads to rapid corrosion of one of the metals on account of potential differences between them. Metal prepared by electro-deposition is usually very hard and brittle, probably because it contains occluded gases; thick coatings may therefore, under certain circumstances, be undesirable. Electro-deposited metal, if it is sound, may generally be rendered soft and ductile by suitable annealing.

(iii.) *Machining, Grinding, Fitting, etc.* — Metal may fail through unsuitable treatment during the mechanical operations of fitting it into finished structures, machining, etc. For example, hardened steel may crack during grinding if grinding be "forced" to such an extent that severe local heating occurs; the metal becomes tempered locally, and severe stresses are set up on account of the partial transformation of the steel in the tempered portions. A glazed grinding wheel has little cutting action, but causes the metal to "flow," heat being developed locally during the process, with a similar result. Machining with an unsuitable tool, with a blunt tool, or with too deep a cut may tear the surface of the metal and start a crack; this should be specially avoided in the case of steel which is to be hardened subsequently, since surface defects of this kind are a frequent source of hardening cracks.

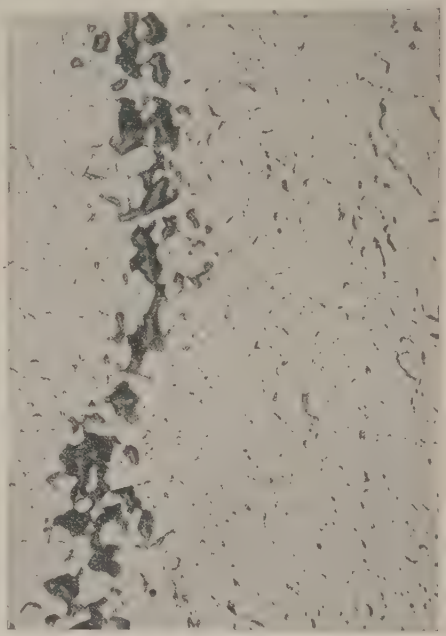

FIG. 6.—Oxide entangled in Weld.

§ (7) THE FAILURE OF METALS.—Failure of metal articles is by no means always caused by pre-existing defects in the material; failure may be due to faulty design and bad workmanship, to careless operation of machinery, to improper conditions of service, or to pure accident, and it is frequently a matter of difficulty to ascertain, by an examination of the material after failure, to which of these causes the result must be ascribed. In the first place, the question of design must be considered, and under this heading may be considered the mechanical details of the article and the kind of material used. A designer is frequently in difficulty because it is not possible to calculate the stresses to which a metal will be submitted in service, so that the choice of material becomes a matter of judgement, or of trial and error. Faulty design is indicated when the same type of failure occurs at the same place in the same article under the same conditions of service, and in such a case the details of the design must be altered, or a material must be found which will stand up to more severe conditions.

With regard to the material itself, with which we are more particularly concerned, certain rules have been more or less generally accepted. It is now realised that metal which has been cold-worked is not reliable under certain conditions. Rosenhain states that "when strain hardness is merely to provide stiffness and does not involve the general question of resistance to serious and continued stresses it is perfectly logical and rational. In some cases, particularly wire, the artificially induced strength appears more or less permanently reliable, although with wire ropes subjected to repeated bending fatigue failures occur, as against alternating stresses strain hardness is of no avail. This is more serious with rods of hard-drawn or cold-drawn alloys employed for bolts, or where called on to carry important loads. Practical experience in such cases confirms conclusions drawn from research data that the extra strength from strain hardness cannot be safely relied on for continued resistance, particularly where

stresses are alternating or intermittent. The best recent practice shows a strong and highly rational tendency to avoid the use of any material which has been severely cold-worked, unless subsequently annealed to remove strain-hardening more or less completely."

It is usually assumed that, provided that it can be obtained without serious reduction of hardness and strength, a ductile material—that is, one which possesses a good extension in a tensile test—is preferable to a material of low ductility; and experience bears out the truth of this view. It is held by some that ductility is of little value in a material which is intended to be stressed only within its elastic range, and that undue consideration is given to this property. Nevertheless, it is probable that many parts of a machine are, at times, stressed beyond their limit of elasticity in service, even if only for short periods, such as, for example, when taking up a heavy load suddenly. Under such circumstances a material which is able to yield to the stress, even if such yielding is very slight, may not be seriously affected where a material of low ductility would break. The case of a locomotive coupling may be cited; such an article is occasionally subjected to rapidly applied stresses greatly exceeding the normal working load, and such articles gradually extend during use; they must, of course, be removed from service before the extension becomes too great. On the other hand, it is obvious that in such a case ductility must not be obtained at too great a sacrifice of tensile strength, or the rate of extension in service will be increased. The above is rather an extreme case, for more usually appreciable alteration of size would render a part unsuitable for its purpose; at the same time, a slight yielding, without appreciable alteration of size or shape, has undoubtedly saved many metal parts from failure.

In the design of any article the mechanical properties of the metals and alloys used have to be considered, and most calculations have been based on the ultimate strength or breaking strength of the material combined with a numerical factor of safety. A more rational system, which is gradually being adopted, is to base such calculations on the elastic limit or the fatigue range, properties which do measure more closely the value of the stresses which the material will withstand without fracture, at any rate within a reasonable period of service. The elastic limit measures the stress (in tension, compression, torsion, etc.) which a material will withstand without permanent deformation, and is therefore a measure of the steady stress which can be applied with safety. Allowance must, in all cases, be made for local concentrations of stress arising from sharp corners, changes of section, local flaws, etc. Specifications based on the value of the elastic limit are gradually being introduced, and should lead to a much more efficient designing of metal parts. The chief difficulty at present is that the measurement of this property is a long process requiring delicate measuring apparatus, and its adoption as a commercial test is hindered on that account. The service of a metal under alternating stress appears to be measured more closely by the "fatigue range" than by any other property. This measures the value of the alternating stress, which can be applied practically indefinitely without leading to fracture. It is usually considered that if failure of the test piece does not take place after about two million reversals of a given stress the fatigue range has not been exceeded. The determination of the fatigue range is at present a more lengthy and costly operation than that of the elastic limit, and its exact relation to the behaviour of material in service is not yet fully worked out. It does not appear to be related to the elastic limit, as was at one time supposed, but it does seem to give some estimate of the service which can be expected from a material under alternating stress.

The first step in investigating failures is to determine that the material used is suited to the design, or, alternatively, that the design is suited to the class of material. In determining this, other properties than those mentioned may have to be considered—as, for example, the hardness, resistance to wear or corrosion, stability (tendency for properties to alter spontaneously), etc.

The next step is to determine, if possible, whether failure is due to the use of defective material or to abuse in service, that is, to being submitted to conditions for which it was not intended. Abuse in service may be impossible to detect; for example, a gear wheel may break through being overloaded momentarily, or a condenser tube may corrode through temporary obstruction which is subsequently removed. The causes in such cases are very difficult, if not impossible, to determine. In other cases, however, abuse in service has local effects on the metal which serve to indicate the cause of failure. A slipping driving-wheel may heat the surface of a rail to a temperature above its critical range, when the rapid cooling, due to conduction of the heat to neighbouring parts, may produce a hardened skin, in which cracks readily form and spread through the material; a white-metal bearing may be allowed to run hot, so that the metal melts: such cases are easily detected.

The first step in the investigation of a case of failure is naturally an examination of the conditions under which failure occurred.

Much valuable information is frequently lost because the conditions at and immediately preceding the failure are not carefully examined. If failure has taken place through the fracture of a part, the fracture should be examined with the least possible delay, especially in the case of metals and alloys which are subject to rapid corrosion, such as steel. The character of a fracture frequently indicates the manner in which the metal was broken, and in some cases gives a general indication of the type of structure of the material. For example, a "fatigue fracture" has a characteristic appearance. The point at which the crack started can usually be detected, as can the path of the crack, from this point up to the time at which final fracture by rapid rupture of the metal commenced. Observation of the point at which fatigue fracture commences may lead to the detection of faulty design. A "crystalline" fracture (one containing bright facets along which rupture of the crystals has occurred —not an "intercrystalline" fracture) indicates by the size of the facets the general size of the crystal structure of the material. Such fractures are generally only found when rupture of the metal has been rapid, and are frequently associated with metal in a somewhat weak and brittle condition. Intercrystalline fracture, in which the path of rupture passes between the crystals, is not so commonly met with. This type of fracture often occurs when metal is broken near its melting-point, or when brittle constituents or impurities occur in the boundaries of the grains; it is also characteristic of metals which have failed by "season cracking." In the latter case fracture is usually a slow process, and may take place gradually over a period of months or years. Fibrous and laminated fractures are found in worked material, and the direction of the "fibres" or "lamination" indicates the direction in which the metal has been extended. A rolled bar, for example, will have a fibrous fracture if it is broken in a plane at right angles to the direction of extension, but will have a laminated fracture if broken in a plane parallel to the direction of extension of the metal.

Fractures should be examined for flaws, blowholes, and other defects which may give an indication of the cause of failure. Discoloration of the whole or a portion of the fracture may indicate that it occurred while the metal was hot; corrosion may indicate that a crack had existed for some time previous to failure having taken place; local variations in the type of the fracture may indicate corresponding variations in the structure. *Fig.* 7 is taken from a piece of fractured mild-steel tubing, the fracture of which was coarse-grained near the surface of the metal but fine-grained in the interior. The microstructure of the junction between coarse- and fine-grained fractures is illustrated. A coarse-grained fracture in a fine-grained material indicates that the crack occurred at a stage in the history of the metal when a coarse structure existed, which has subsequently been removed by heat treatment.

FIG. 7.—Large Ferrite Crystals at Surface of Steel Tube.

Further examination of a material will usually take the form of the determination of the chemical composition and essential mechanical properties, to determine whether it is of the required quality and has the necessary properties. At the same time an examination of the structure will reveal the constitution and, as a rule, the thermal and mechanical treatment to which the material has been subjected. These three methods of investigation are those most frequently used in the examination of any case of failure. In some cases examination by one method will suffice; more usually information from all methods of examination is necessary for a complete solution. Chemical analysis, by itself, is only of value in dealing with specific materials whose properties are definitely known, and on which the effects of variations of composition and certain definite impurities have been deter-

mined. In the case of some well-known alloys, such as steel, brass, and a few others, chemical analysis alone will occasionally, though not frequently, indicate the cause of failure. Mechanical tests determine certain specific properties of a material irrespective of its microstructure and composition, and may be sufficient in certain cases in which the nature of the applied stress during service is known. Taken in conjunction with a knowledge of the chemical composition of a material, mechanical tests may sometimes be used to detect failures due to cold-working; sometimes they will show up cracks and flaws, while, in a general way, an examination of the fractures of test pieces will give general indications of the quality of a material. For a definite determination of the cause of failure examination of the structure of the material is usually essential. The properties of a material depend on its mechanical and thermal history, since this determines the condition in which it exists at any moment. Examination of prepared surfaces, together with the use of suitable etching reagents, will sometimes reveal in a very complete fashion the essential portions of the history of a metal from the time it was molten until it became a finished article. The use of special etching reagents for revealing coring and segregation, such as the cupric reagents for steel, gives a method of tracing the manner in which the material has been deformed during the various processes of manufacture, while the examination of the existing structure indicates the treatment to which it has been submitted during the final stages. Sometimes the essential features of the last three or four stages of manufacture are written in the microstructure of the sample. In other cases local defects, due to improper methods of casting, working, or heat treatment, or to severe conditions, or abuse in service, are detected with a certainty which is impossible with other methods. No very general rules of procedure can be indicated here, since the methods adopted must be suited to the material under investigation and to the conditions of service. The methods of detecting certain types of defect have already been indicated in a previous portion of this article.

In cases in which some doubt arises as to the suitability of a certain structure for a certain purpose, comparison with articles which have given good service may be made; in other cases, in which the mechanical or heat treatment is not clearly indicated, further information may be obtained by experimental treatments, carried out in the laboratory, combined with a determination of the mechanical properties of the treated material. Finally, in all investigations into the structure and properties of metal articles, due consideration must be given to the conditions under which they are made, and to the properties which can reasonably be expected in the material under manufacturing conditions. Particularly is it necessary to take into consideration the size of an article in relation to the treatment to which it must be subjected, for the properties which can be obtained on small samples treated in a laboratory are often very different from those which can be obtained in a large sample under manufacturing conditions.

D. H.

METALS, MICROSCOPIC EXAMINATION OF

The microscopic examination of metals, initiated by Sorby of Sheffield about the year 1861, has developed in recent times into an increasingly important means of studying the internal structure and constitution both of pure metals and alloys. In conformity with its growing importance, this method of investigation has developed a highly-specialised technique. The specialised character of the methods employed arises in the first instance from the fact that the very great opacity of metals makes it practically impossible to cut or otherwise prepare satisfactory sections thin enough to be examined by transmitted light. The microscopic methods employed must therefore be adapted for dealing with opaque objects viewed by reflected light. This requirement has led to the development of a special type of "metallurgical" microscope. On the other hand, the preparation of metal specimens for examination by reflected light has brought with it the development of methods for the preparation of metal surfaces free from defects which would obscure the structure to be studied, and of means of developing upon a smooth, polished surface a pattern easily visible under the microscope which reveals the internal structure of the material under examination. It will be convenient first to consider the preparation of the metal surface for examination, since this will furnish the information upon which the design of the specialised features of metallurgical microscopes is based.

§ (1) Preparation of a Section. — The first step in the preparation of a metal microsection consists in selecting the specimen of metal to be prepared and examined. This must depend to a very large extent upon the precise nature of the piece of metal from which the specimen is to be prepared and also upon the purpose in view. A satisfactory selection can indeed be made only in the light of full knowledge of the peculiar features likely to be encountered in each type of material. Thus in a casting the microstructure will differ materially according as we examine a section from an external region where cooling has

been fairly rapid, giving rise to a radiating structure of elongated crystals generally termed the "chill" structure, or from an internal portion where temperature gradients were slight during freezing, and the crystals show nearly equal lengths in all directions. In wrought metal, on the other hand, which has undergone such operations as forging or rolling, attention must be paid to the direction in which the material has been elongated. Here longitudinal and transverse sections may give widely different appearances. A particularly important point in this connection is that sections cut parallel to the direction in which elongation has taken place may become practically unintelligible if taken in such a way as to cut, at a very small angle, through layers of a structure which has been flattened out into thin sheets. In such sections the structural outlines become extremely confused and irregular simply because of the obliquity of the plane of section. As a general rule sections cut from a given piece of metal in several different directions should be examined.

The method by which a piece of suitable size for subsequent operations is detached from the larger mass of metal is of considerable importance. A good deal depends upon the hardness and general character of the metal in question, but except in very hard, non-ductile materials, where pieces are best removed by being forcibly knocked off by a suitable blow, it is advisable to employ the most gentle means available. The use of sharp cutting-tools, such as drills and saws, is, as a rule, quite satisfactory, but the use of more forcible rapid methods is to be deprecated, since alteration of the structure of the metal, as the result of violent mechanical treatment, may occur, and this may in certain cases tend to vitiate the results of subsequent microscopic examination. Even the use of powerful cutting-tools may cause difficulty, since it is found that in many metals they produce a plastic deformation of the microstructure to an appreciable depth below the finished surface of their cut. Thus a surface which had been prepared by means of a heavy-cutting, coarse file is apt to show, in the finished stage, lines or bands of distorted structure which are in reality traces of the deepest of the file-marks. Still more objectionable from the point of view of microscopic examination is the practice, which is now becoming widespread, of cutting up metal by means of the oxyacetylene cutting-blowpipe. In steel particularly, the very high temperature generated locally by the cutting flame is sufficient to produce changes in microstructure over a surprisingly wide area. Care must therefore be taken that any specimen used for microscopic examination has been taken from a spot sufficiently removed from the path of any cutting flame which may have been employed.

The preparation of a specimen for microexamination, after it has been cut to a suitable size, generally begins by some process of grinding or filing, serving to produce upon it one plane face. As a rule, this operation is done very roughly, with the result that the surface produced is by no means plane but usually markedly convex. This is a distinct disadvantage, not only in the finished specimen but also as a retarding factor during the subsequent more delicate stages of preparation. Where possible, therefore, this preliminary shaping should be done in a machine-tool giving a plane surface. If this is not possible, a fairly satisfactory result can be obtained by means of a wide flat file. For this purpose the file should be held stationary in a horizontal or nearly horizontal position, and the face of the specimen should then be rubbed firmly over the surface of the file. By this means a reasonably flat surface can be obtained much more readily than by the more usual process in which the file is drawn over the specimen. Whatever method of filing or grinding is employed, however, care is required to avoid any appreciable heating of the specimen. The heat which can be evolved by the over-vigorous grinding down of a specimen of hardened steel, for instance, is quite enough to bring about very important changes in its microstructure. In any case, however, heating is a sign of excessive violence, and should therefore be carefully avoided.

When the specimen has been provided with a reasonably flat surface, free from the coarser tool-marks, the process of fine grinding may be commenced. For this purpose, the surface is rubbed on a piece of fine emery paper, care being taken to move the piece of metal backwards and forwards parallel to itself. If this is done, the surface rapidly becomes uniformly covered with a system of approximately parallel scratches corresponding in depth and width to the grade of emery employed. By looking at the surface in such a way that the light falls along the length of the scratches, any remaining marks running in other directions are at once detected, while amid a maze of curved and intersecting scratches it would be impossible to detect any but the coarsest of "odd" markings. When the process of rubbing down on the first grade of emery has been carried so far that no other markings than the parallel scratches due to that rubbing itself can be seen, the specimen is transferred to the next finer grade of emery paper, care being taken that no grains of the coarser kind are carried with the piece of metal. Rubbing is again carried out by approximately parallel motion, but the direction is now chosen

approximately at right angles to that of the previous system of scratches, and rubbing is continued until no trace of the previous, coarser, system remains. This process of successively reversing the directions of the systems of scratches on successively finer grades of emery paper is continued until the last set of scratches are extremely fine. For this purpose it is usual to employ the specially fine French emery papers prepared originally for the use of engravers, but now regularly supplied for metallographic purposes. Still finer grades of emery paper can be prepared by the careful levigation of fine emery powders, and the subsequent coating of such extremely fine powder upon strips of parchment previously rendered adhesive by a thin coating of white of egg. This refinement, however, is rarely necessary.

When scratches on the surface of a moderately hard metal have been reduced to a sufficient degree of fineness, they can be readily obliterated by a brief polishing operation. Polishing, in practice, usually consists in rubbing the surface more or less rapidly against a smooth, soft surface, such as that of a fine cloth, which is charged with some polishing medium, such as rouge or alumina, and moistened with water. While it is distinctly preferable that all the grinding operations with the finer grades of emery paper should be carried out by gently rubbing by hand alone, polishing is best done by means of discs covered with the cloth or other medium employed, and driven by mechanical means at some definite speed, the harder metals permitting of the advantageous employment of higher speeds. If both the surface of the specimen and the revolving polishing disc are in proper condition, the obliteration of the fine scratches left from the last stage of emery grinding should not occupy more than four or five minutes, but difficulties are often encountered. Thus the surface of the specimen may be found to be traversed by a number of scratches deeper than those due to the finest grade of emery employed, and it may prove difficult, if not impossible, to polish these out in any reasonable time. It is undesirable practice to endeavour to do this. For many purposes a few more or less isolated scratches are of no importance, but if they are to be removed it is far better to return to a suitable grade of emery and to grind them out in that way. Prolonged polishing, particularly if pressure is applied against the polishing disc, produces a surface which is unsatisfactory for metallographic purposes.

The extreme case of a "polished" surface which is undesirable for microscopic examination is that produced by a burnishing process, in which the finely ground surface of the metal is rendered smooth and bright by the pressure of a smooth, hard body, such as a hard steel burnisher. Here the surface irregularities are not removed, but the metal is forced, by great intensity of local pressure, to flow over and into them. The surface is thus covered by a "flowed" layer whose chemical behaviour and microstructure do not correspond with those of the interior of the metal. To some extent, as has been shown by Beilby,[1] such a burnishing action, resulting in surface flow, always occurs when metal—or indeed any substance—is polished. But when only light pressures and suitable polishing materials are used the amount of this surface flow can be very much reduced, so that the flowed layer is readily removed by the subsequent etching process, which then reveals the true structure of the metal. Evidences of surface flow, however, frequently make themselves felt. Thus it is a common experience to find that an apparently perfectly polished specimen, quite free from scratches or other defects when it leaves the polishing pad, yet exhibits a maze of scratches after it has been etched. At first the operator is inclined to believe that he must, inadvertently, have scratched the surface during the etching operations, but he soon finds that when such a possibility has been entirely eliminated, the scratches still reappear after etching. The explanation is that these scratches have never been removed by the polishing process, but have merely become filled up, or even covered over, by the flowed surface layer. When this layer is dissolved away by the etching reagent the scratches are again uncovered. If they are again polished away on the pad they will still reappear to a slight extent on subsequent etching, but a few repetitions of this process will bring about their entire removal. For further very complete evidence on this matter, reference should be made to the original papers of Beilby, already cited.

The technique of the polishing process depends mainly upon meticulous care to avoid the intrusion of foreign matter, which is, as a rule, sufficiently hard and "gritty" to cause scratching of the delicate metal surfaces on the polishing pad. Extreme cleanliness and care, resembling those employed by bacteriologists in avoiding bacterial contamination, are thus required. For the best kinds of work it is even necessary to keep a separate polishing disc for each metal to be examined, as a disc on which steel has been polished is not satisfactory if used for copper or aluminium, or *vice versa*. The material of the pad or disc must also be chosen with great care. Thick woollen cloths such as those used for making liveries are very suitable, but a satisfactory grade should be selected by trial, and when a

[1] Beilby, *Roy. Soc. Proc.*, May 1903, lxxii., and 1909, lxxxi.; *Soc. Chem. Industry J.*, Nov. 1903.

suitable kind has been found a considerable quantity should be obtained, since by no means every sample, nominally of the same quality, answers equally well. The use of this cloth has the disadvantage that its soft thickness produces a certain amount of erosion in the specimens, the softer constituents being removed rather more rapidly than the hard. Chamois leather stretched over a metal disc is better from this point of view, while fine calico, taken from old, worn garments, has proved particularly satisfactory. For the purpose of polishing-powder a large variety of substances, usually metallic oxides, have been employed, iron oxide (rouge) being most frequently used. Le Chatelier, however,[1] has shown that both alumina and chromic oxide, when prepared in special ways, are far superior to rouge. The present writer, on the other hand, has found calcined magnesia (heavy) one of the best and most readily obtained polishing media.

When the specimen has been provided with a satisfactorily polished surface, it should—in ideal conditions—show a perfectly featureless blank when examined under the microscope. Actually, particularly if oblique illumination is employed, this is never the case. Small defects and a few scratches, however, do not seriously interfere with the use of the section, except where photomicrographs are to be taken. Even for that purpose, however, a certain amount of scratching must sometimes be reluctantly admitted, since with the softer metals it is practically impossible to eliminate such defects. Apart from such features, however, a well-polished specimen, as a rule, shows no marked indication of the structure of the metal, except in cases where very hard constituents are present or where the polishing process has been carried out in a manner specially calculated to cause erosion or, as it is termed, "relief polishing." In the vast majority of cases, therefore, it becomes necessary to "develop" the surface by producing upon it a microscopically visible pattern which shall indicate the structure of which the polished surface is a section. This process of revealing or developing the structure is termed "etching"; it is generally carried out by the action of a weak acid or other reagent, which slowly and gently attacks and dissolves the metal, producing upon the surface a slightly dulled or "etched" appearance.

§ (2) Etching — the Reagent. — The manner in which an etching reagent reveals the internal structure of a polished specimen depends upon the nature both of the metal and of the reagent employed. Metals, from this point of view, fall into two great classes according as their microstructure exhibits a single homogeneous phase or consists of two or more chemically and physically distinct phases or microconstituents. In the former case the metal is an aggregate of crystals all of the same chemical composition, and, if their presence is to be rendered evident by etching, the chemical attack must be of such a nature that it reveals the minute differences between adjacent crystals. These differences are presumably due to the fact that the angle at which the surface of the polished section cuts the space-lattices is different in each crystal, and there appears to be a corresponding difference in the rate at which each crystal is attacked by weak solvents such as dilute mineral acids. In some circumstances a slight difference in the rate of attack is all that is observed, and in that case the etching effect is of a very simple nature: adjacent crystals being dissolved away to slightly different depths, a small difference of level is produced at the boundary where they meet. This implies the existence of a small sloping surface which, under normal illumination, appears as a black line, whose thickness will depend solely upon the difference of level which has been produced. Iron (ferrite), when lightly etched with picric acid, gives a result of this kind. In the majority of cases, however, this attack on different crystals brings about not only a general dissolving away of the surface, but also a certain roughening of that surface. This arises from the development of large numbers of minute facets which bear some definite relation to the crystal structure. When etched in this way the various crystals appear shaded to different depths when viewed with normal illumination, and exhibit the typical "oriented lustre" of etched crystalline solids when viewed under oblique light.[2] In some cases the etched facets on crystal surfaces become large enough to be individually resolved by the microscope, and in other cases they appear as more or less isolated markings on the crystal surface. In the latter case they exhibit the typical geometrical characteristics of the crystal, and are known as "etch figures." In other cases, again, the etching of a single-phase metal or alloy may be so conducted that there is relatively little dissolution of the crystal surfaces, but a concentration of chemical action at and near the crystal boundaries. Under such a reagent these boundaries become widened into grooves or even bands.

The etching process in a duplex or multiplex alloy is of an essentially different type. Here there is a definite difference in chemical composition and chemical properties between the constituents, with the result that, as a rule, one of them only is attacked by the etching

[1] Le Chatelier, *Rev. de Métallurgie*, 1905, ii. 528.

[2] For a fuller account of these phenomena, see article on "Metals and Alloys, Micro-structure of."

reagent, the other being protected in a manner which may be regarded as electrochemical. The latter view is borne out by the fact that in almost every case one particular constituent of an alloy is preferentially attacked, whatever the reagent employed. It is a further consequence of the chemical differences between diverse constituents in an alloy that, as a rule, the etching process is much more rapid in a duplex alloy than in a single-phase material. Weaker etching reagents and shorter times of exposure must therefore be employed. Further, it is not, as a rule, possible to observe the typical "oriented lustre" of such sections under oblique illumination, except in cases where the deep-etching constituent predominates and itself possesses crystalline orientation capable of being developed in this way.

A very wide range of chemical substances have been employed as etching reagents for various metals, and it would be beyond the scope of the present article to attempt to enumerate them and their peculiarities. Only a few typical examples will therefore be mentioned.

(i.) *Acid Reagents.*—By far the most widely used etching reagents are the acids, which are employed in various degrees of dilution. Thus for iron and steel nitric acid is frequently used. It has even been used in the concentrated form, which renders a polished steel surface "passive." If the strong acid is washed away rapidly in a stream of water, however, action occurs for a brief period, and this has been recommended for etching steel. A more usual and much safer plan is to immerse the specimen in a bath of dilute acid, the dilution varying from 10 per cent to 0·1 per cent, the diluent being either water or alcohol. In the case of wrought iron or very mild steel this reagent readily reveals the crystal boundaries while roughening and darkening any pearlite areas present rather too deeply. There is also an undesirable tendency, particularly in aqueous solutions, to produce a darkening — probably due to oxidation — of some of the crystals. As a result of these effects, nitric acid, and also the other strong mineral acids, are now widely regarded as somewhat crude reagents whose indications cannot always be trusted, particularly in regard to steel. For many metals and alloys, particularly those resistant to chemical action generally, these powerful acids are almost the only means of etching available. For iron and steel, however, numerous other reagents have been used with great success. These include particularly a number of organic acids, among which a solution of picric acid (trinitrophenol) in alcohol has found very wide application. This reagent, which may be used either as a 4 per cent solution in alcohol, or as a saturated solution in the same solvent, gives results of great clearness and uniformity, and allows the depth of etching to be varied very readily at will. This is of special importance where very high magnifications are to be used, since for this purpose a much slighter amount of etching must be employed than is desirable for use with lower magnifications. Thus a specimen of mild steel may require etching for 10 seconds in alcoholic picric acid if intended for examination at 150 diameters, but needs only one or two seconds' exposure to the same reagent if intended for study at 1000 diameters magnification.

The acids and similar reagents referred to above produce their etching effects mainly by virtue of the fact that they attack or dissolve the various constituents of the metal at different rates, and thus produce differences of level and texture which build up the microscopic pattern indicative of the structure. In some cases solutions of salts which enter into reaction with the metal may be employed in a precisely similar manner, but in other cases their mode of action is different. This applies particularly to cases where the result of etching is to deposit a thin film of coloured material upon certain of the constituents of the specimen, thus bringing about the development of a pattern essentially different from that due to alterations of level. The most striking example is furnished by the so-called "cupric" reagents now widely employed in the study of steel. It has been found [1] that various solutions containing a small amount of a cupric salt react with a steel surface in such a way that a deposition of a small amount of copper takes place. Where the quantity of copper deposited is relatively large, it first covers the entire surface of the steel, and must then be rubbed or brushed off. If this is done, a mere "difference of level" effect is left behind, although the method is useful for producing broad effects serving to reveal the general scale of the structure, and particularly the distribution of impurities, etc. If, on the other hand, the concentration of the copper salt in the solution is low and suitable restraining agents are present, the deposition of copper is very slight in amount, and it then takes place in a preferential manner, indicating the distribution of certain dissolved impurities, such as phosphorus, in a very striking and useful way. The exact interpretation of the etching effects produced by these reagents in steel is, however, still the subject of further research.

[1] Rosenhain and Haughton, *Iron and Steel Inst. J.*, 1914, i.; Stead, *Cleveland Inst. Mining Eng.*, Dec. 1914; Le Chatelier, *Comptes Rendus*, 1915, clxi. 373, and 1917, clxv. 349; *Rev. de Métallurgie*, 1918, xv. 127; *Comptes Rendus*, 1918, clxvii. 472; *Whiteley, Iron and Steel Inst. J.*, 1921, i.

Other substances employed as etching reagents also produce surface deposits or stains. Thus a boiling solution of sodium picrate when applied to steel produces a dark staining effect on any free cementite which may be present, and thus serves as a valuable means of identifying this constituent. Special reagents for the identification of other constituents met with in steel have also been proposed, but their application is less definite, mainly perhaps because the very "constituents" which they are intended to identify are essentially of the nature of ill-defined transition products.[1]

(ii.) *Other Methods.*—Among the methods which have been employed for the purpose of producing "etching" effects by surface staining is one which, while not of great practical value, is of special interest. In this method the wide differences in magnetic permeability which exist between the different constituents of steel are utilised. The specimen is magnetised by means of not too powerful a field, and is then brought into contact with a medium from which finely divided iron is readily deposited. This iron is deposited preferentially on those portions of the surface where there is the greatest magnetic flux, and the most highly permeable constituent is thus coated or "stained" with finely divided iron. For this purpose, however, it is desirable to employ a colloidal solution of iron which is best capable of supplying the metal in a state of sufficiently fine division.

It has already been indicated that the reactions which occur in most etching operations are to a considerable extent electrochemical in nature, but, as a rule, their intensity is governed mainly by the concentration and the temperature of the reagent employed. In some cases it is desirable to carry the control of the process much further. Thus it may become desirable to make the etching process sufficiently slow and regular to make it possible to keep it under observation by means of the microscope. This is desirable where it is important to establish some definite connection between a pre-existing feature and a subsequent etching effect. This can sometimes be done very satisfactorily by using an ordinary etching reagent, such as dilute nitric acid, but rendering the solution viscous, and thus retarding the action by employing glycerine instead of water as the solvent or diluent. A much more generally applicable method of regulating the etching process, whether it be desired to make it very slow or otherwise, is to make the specimen the anode in an electrolytic cell and to apply any desired voltage. If an electrolyte is used which is itself without any appreciable action on the metal specimen, then the solvent action on the specimen depends entirely upon the quantity of electric current passed through the cell, and can therefore be very accurately regulated and reproduced whenever desired. The electrolytic method has the further very great advantage that by its aid practically any metal or alloy can be successfully etched, even when the material is highly refractory in its behaviour to chemical reagents. It appears probable that this method of etching will find increased application among those metallurgists who have the necessary appliances at their disposal.

(iii.) *Gaseous Reagents.*—While, as a rule, etching reagents are applied to the surface of a metal specimen in liquid form, there are certain gaseous or vapour reagents which also serve important purposes. The most widely practised method of gaseous "etching" is one first employed by Stead,[2] and generally known as "heat-tinting." Here the specimen, usually steel, is first carefully cleaned and dried and — preferably — very lightly etched with a dilute mineral acid. It is then gently and uniformly heated, preferably on an electric hot-plate. The surface of the metal then undergoes gradual oxidation, accompanied by the formation of the well-known coloured films which have so long been utilised in the workshop tempering of steel tools. On microscopic examination, however, it is found that the oxidation is not uniform over the entire surface, but has taken place differentially as between the various constituents present, thus producing a species of "etching." Where phosphorus is present in iron and steel brilliant effects of this kind are produced, the indications being, in many cases, exactly similar to those obtained by means of the "cupric" reagents described above. In addition to the use of the oxygen and water-vapour of the air, it is possible to utilise other gases or vapours for the purposes of etching, either in the cold or, as in ordinary heat-tinting, at slightly elevated temperatures. Sulphide of hydrogen or of ammonia can be employed with some metals, while ammonia acts upon others. Chlorine and hydrochloric acid have been used by Baykoff,[3] among others, for the etching of steel specimens at high temperatures above the critical range. The object of such high-temperature etching, which was first attempted by Saniter[4] with fused calcium chloride as an etching reagent, is to determine the microstructure of steel (or other metals) at high temperatures. For this purpose it is not essential that the specimen should be actually examined with the micro-

[1] Kourbatoff, *Rev. de Métallurgie*, 1905, ii. 169, and 1906, iii. 648.

[2] Stead, *Iron and Steel Inst. J.*, 1900, ii.
[3] Baykoff, *Rev. de Métallurgie*, 1906, vi. 879.
[4] Saniter, *Iron and Steel Inst. J.*, 1897, ii.

scope while hot, although more or less successful attempts to do this have been made by several workers. The essential point is that etching shall take place at the temperature at which the structure is to be studied. When this occurs a surface pattern is produced which corresponds to the hot structure, *i.e.* to the structure which existed at the moment when etching occurred. Subsequent changes in the metal can only affect this surface pattern in a secondary manner, and the main features of the etching pattern produced at the high temperature can be readily seen when the specimen is subsequently examined in the cold state. There is, however, in the use of gaseous reagents at high temperatures, an essential condition. Unless it is merely desired, as in ordinary heat-tinting, to study some differentially produced surface layer or film, it is necessary that the product which results from the reaction of the gaseous reagent with the metal shall also be gaseous at the temperature employed. If this is the case, the surface of the metal is left clean and suitable for the microscopic examination of the etching pattern produced by the chemical action which has occurred. If the reaction product is not volatile, on the other hand, the metal surface is left covered with a coating—generally rough and irregular—of this product, which entirely hides the real etched surface. In the case of iron and steel, etching at temperatures above 800° C. can be well carried out by means of chlorine gas, because the ferric chloride produced is volatile above that temperature. At lower temperatures, however, the specimens become useless owing to the presence of layers of chloride.

In this connection reference must be made to a curious phenomenon, whose true nature is not yet fully understood, which is encountered when polished-metal specimens are raised to high temperatures, either in a good vacuum or in an atmosphere of "neutral" gas, such as hydrogen or nitrogen. In these circumstances it is quite possible, although by no means easy, to preserve the polished surface of the specimen from oxidation or other tarnish, but even when no sort of chemical action is possible—as in a very high vacuum—the metal surface does not remain smooth and unaltered, but, on the contrary, it develops very well-defined patterns, generally known by the name of "heat reliefs." These obviously correspond to the internal structure of the metal, as the crystal boundaries of a pure metal become clearly revealed in this manner. In some cases, indeed, where a metal undergoes an allotropic transformation involving a crystalline rearrangement two or more sets of boundaries appear in the heat-relief, corresponding to these successive conditions.[1] In some metals, such as silver and zinc, there can be little doubt that this vacuum etching is in reality due to a slight volatilisation of the metal, which occurs preferentially at the crystal boundaries;[2] but in the case of iron and copper this explanation is not so readily acceptable, particularly as the pattern appears to be due rather to the development of differences of level than to local removal of material. It has been suggested that differences of expansion between adjacent and differently oriented crystals may produce an up-thrust upon some of the crystals which may not only reveal the boundaries of the surface layer of crystals but may even show traces of the boundaries of the crystals immediately below. Sometimes a double system of clearly defined boundaries can be produced upon a surface which has not been exposed either to chemical action or to volatilisation; an example of this kind occurring in a specimen of cadmium, which has been prepared by dropping a little molten cadmium upon a warm glass plate and allowing it to cool in contact with the glass, has been studied. Here one set of boundaries appear to be mainly due to the presence of gases or water-vapour on the glass surface. These have been entrapped by the growing crystals and have formed minute channels in the surface at the crystal boundaries. The second set of boundaries, however, are of an entirely different nature, but their real mode of origin, like that of heat-reliefs in general, is not fully elucidated.[3]

(iv.) *Polish Attack.*—Before leaving the methods by which the microstructure of a specimen of polished metal can be revealed, reference must be made to certain mechanical means whereby this can be accomplished. In connection with the polishing operations described above, mention has been made of the process of "relief polishing" whereby the harder constituents are left standing up in relief against their softer surroundings. As a rule this process is somewhat undesirable, since it generally furnishes specimens requiring undue depth of focus and having rounded or vague outlines between adjacent constituents. In some cases, none the less, relief polishing furnishes one of the best methods of developing a structure, but, as a rule, it is accompanied by a small amount of chemical attack produced by adding to the polishing medium a small proportion of some mild etching reagent. This is the method of "polish attack" so

[1] Rosenhain and Humfrey, *Roy. Soc. Proc.* A, 1909, lxxxiii., and *Iron and Steel Inst. J.*, 1913, i.; Rosenhain and Ewen, *Inst. of Metals J.*, 1912, ii.; Robin, *Bulletin de la Société d'Encouragement*, Aug. 1912 and March 1913.

[2] Rosenhain and Ewen, *Institute of Metals J.*, 1912, II. xii.

[3] Ewing and Rosenhain, *Roy. Soc. Phil. Trans.* A, 1900, 269.

successfully practised by Osmond [1] and others in the study of steel. This combination of very gentle polishing and very mild chemical action has the advantage of bringing up a minute and delicate structure with special clearness. It has the great disadvantage that it is a very delicate process, in the course of which a specimen is easily spoiled by the least lack of extreme care. It is also somewhat slow and comparatively uncertain, so that it is not widely practised at the present time.

The structure of a reasonably ductile metal can, however, be revealed or "developed" on a polished surface by the application of a slight amount of plastic strain or deformation. Thus if a piece of lead is prepared with a bright surface—as, for instance, by allowing it to cool from fusion in contact with a smooth polished surface, such as that of glass, mica, or even polished steel—the microstructure can be immediately developed by slightly bending the piece of lead backwards and forwards, leaving it, at the end, as nearly flat and straight as possible. As a result of the plastic strain applied to the metal the crystal boundaries are revealed as black lines (seen under normal illumination), while the surfaces of the crystals themselves are cross-hatched with innumerable slipbands. (See article on "Metals, The Relations of Strain and Structure.") The crystal structure thus revealed corresponds precisely with that which can be developed on the same surface by etching it with dilute nitric acid. A similar effect can be produced on a polished piece of iron or very mild steel, or in copper or brass. When a duplex alloy is treated in this way, however, a somewhat different effect is produced; the slip-bands within the crystals are not nearly so conspicuous, while, on the other hand, the duplex structure of the alloy becomes clearly evident by the differences of level and of deformation which arise between two constituents which generally differ widely in hardness. A typical example may be found in the eutectic alloy of lead and tin, whose very minute microstructure is most beautifully developed by the application of plastic strain.[2]

§ (3) Mounting and Levelling.—When a specimen has been satisfactorily polished and etched, the next step in its preparation consists in so mounting it that it can be conveniently examined under the microscope. There is one type of metallurgical microscope for which it is claimed that no mounting of the specimens is required, but if advantage is taken of that feature, the delicate polished and etched surface of the specimen must be allowed to rest upon a glass or metal surface of the microscope, and for many purposes this is not admissible. For the majority of microscopes it is essential that the specimen should be mounted on a flat slip of glass, wood, or metal in such a way that the polished and etched surface is parallel to the underside of the slip. Such mounting may be effected in many ways, ranging from the roughest adjustment by unaided hand and eye to careful instrumental setting. As a rule the specimens will not be plane-parallel slices, since their preparation in that form involves a considerable amount of needless labour. When the underside of the specimen is rough, however, it is convenient to attach it to the mounting-slip (usually of glass) by means of some soft, plastic material in which the specimen may be bedded and then adjusted into its proper position. Soft wax or "plasticine" is now very widely employed, but plaster of Paris of fairly slow-setting variety, or even sealing-wax, kept temporarily warm and soft, may be employed. For the purpose of aiding the operator in setting the prepared surface of the specimen truly parallel to the underface of the mounting-slip, numerous mechanical devices have been proposed and employed. One simple method consists in the use of two pieces of metal of exactly equal thickness, or the two may be combined into a single ring or short section of tube, cut with parallel ends. A selection of such pieces, of varying thickness to correspond to specimens of varying thicknesses, must be provided. For the mounting operation the specimen is placed face downward on a flat plate of glass or metal, and the ring, of suitable diameter and height, is placed around it. If separate pieces of metal are used, one is placed on either side of the specimen. A small piece of soft wax or similar mounting material is then placed on a mounting-slip (usually a glass microscope slide), and the slip, with the wax downward, is laid across the ring or the two pieces of metal lying on either side of the specimen. The whole very simple arrangement is shown in the diagram, *Fig.* 1, where S

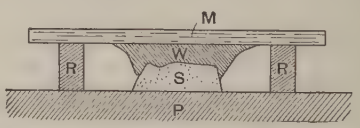

Fig. 1.

is the specimen, P is the flat plate, R, R the ring or metal slips, M the mounting-slip, and W the wax. It will be seen that if M is pressed steadily down, causing the specimen to embed itself in the wax, until M lies upon RR, then the prepared surface of S, in contact with the plate P, will be parallel to the face of M in contact with the distance-pieces or ring R,

[1] Osmond, *Étude des alliages*, 1901, p. 277.
[2] Ewing and Rosenhain, *Roy. Soc. Phil. Trans.* A, 1899, 249.

provided that R is accurately cut with parallel ends. The desired parallelism is, of course, with the other surface of M (shown uppermost in *Fig.* 1), since it is that surface which comes into contact with the stage of the microscope. Care is therefore required to select mounting-slips having parallel surfaces, and since glass slips for this purpose are rarely even approximately flat, this is a distinct difficulty. The method is, at best, not very perfect, and if used without the greatest care is liable to cause damage to the prepared surfaces of specimens, and to mount them at slight angles, owing to the accidental presence of minute particles of foreign matter on one or other of the surfaces which are intended to be set parallel.

In order, mainly, to avoid these difficulties, and also to provide means for much more accurately level mounting, a small optical levelling device has been designed for use at the National Physical Laboratory.[1] In this device, which is diagrammatically illustrated in *Fig.* 2, light from a small source at S is

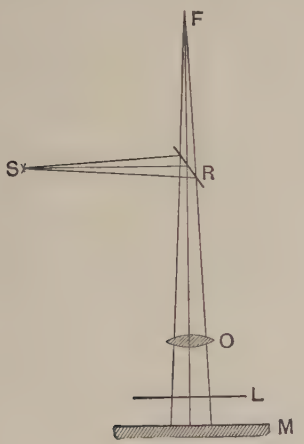

FIG. 2.

reflected downward by a transparent plane-parallel glass reflector R, which forms part of a small autocollimating telescope. The reflected light leaves the objective O as an approximately parallel beam which falls at right angles upon a reflecting surface M, whence it is returned into the telescope and brought to a focus at F, where the image of the source S is seen against a cross-wire in an eyepiece. If now any other reflecting surface L is interposed, and this surface is so set that the image of S again falls on the cross-wire in the eyepiece, it follows that, to a high degree of accuracy, L is parallel to M. In practice M is the silvered underside of a piece of plate glass carefully selected so as to have plane parallel faces. The prepared specimen of metal is first roughly mounted by hand and eye adjustment, on a suitable mounting-slip, and this is placed upon the upper surface of the glass plate just mentioned. The specimen is then adjusted with the fingers until the image reflected from the polished metal surface again falls upon the cross-wire, when the specimen will be accurately levelled. This operation occupies literally only a few seconds. Most specimens, even when etched, give a sufficiently bright reflection to allow of fairly good setting, although a really sharp image is not often obtained. Where more perfect setting is desired a very thin slip of glass, or even mica, may be dropped gently upon the prepared surface of the specimen, when a very good reflected image is immediately obtained. It will be seen that, apart from the refinement of setting just mentioned, this method of levelling avoids all handling of the polished surface and sets the specimen truly parallel to the underside of the mounting-slip. The device has been embodied in a very simple and sturdy instrument.

§ (4) PRESERVATION OF SPECIMENS. — The preservation of specimens of metal prepared for microscopic examination is a matter of considerable difficulty, and for the majority of purposes it is generally found sufficient to prepare a record by photomicrography, and if subsequent re-examination is required to repolish and etch the specimen. Methods of more or less permanent preservation have been tried by various workers, one of the best being to coat the specimens with a thin layer of transparent varnish. Such a varnish may consist of celluloid or collodion dissolved in ether or in amyl acetate. Preferably the whole specimen is dipped in the varnish and then allowed to drain. If the thickness of the residual coating is correctly adjusted, the specimen can be examined under the microscope, even with high magnifications, without appreciable loss of definition resulting from the presence of the coat of varnish. Too thick a coat of varnish, however, is very liable to peel off or to allow air to penetrate between varnish and metal, while too thin a coating shows the bright colours of Newton's rings. There is the further difficulty, which applies to all methods of preserving polished and etched metal surfaces, that it is essential to remove all traces of the etching reagent which has been employed in the preparation of the specimen. This is a matter of very considerable difficulty. The usual procedure is to rinse the etching reagent off with a stream of either water or alcohol, according to the solvent in which the reagent has been applied, and to follow this with a more copious stream of alcohol as free from water as possible

[1] Rosenhain, *Inst. Metals J.*, 1915, i.

("absolute alcohol"). This, in turn, is often followed by a jet of ether, after which the specimen is allowed to dry in the air or its drying may be accelerated by the use of a current of warm air. If the etching reagent and its products of reaction have been removed, and further contamination of the liquids used has been avoided, the specimen thus treated dries with a perfectly clean surface. Ether, however, is extremely apt to become faintly contaminated with greasy matter probably indirectly derived from the hands of the operator, and will in that case leave a thin iridescent film behind. For this reason, washing with ether is often omitted and the specimen dried after washing with alcohol, the drying being aided by very gentle wiping with a perfectly clean soft linen cloth. Even when the washing has been very carefully done, it frequently happens that peculiar marks and patches appear some little time later. This is particularly liable to occur where the specimen contains fissures or cavities of any kind, from which it is almost impossible to remove traces of etching products. These afterwards "creep" out upon the surface by capillary action, and thus form disfiguring marks. Under a varnish coating these generally lead to the destruction of the coating.

Another method of protecting prepared metal specimens is to mount them on glass slips in a fashion similar to that employed by biological workers for their sections. For this purpose a ring is placed round the specimen, which must be cut thin and flat, and a micro-cover-glass is cemented over this ring, thus enclosing the specimen in a gas-tight cell. This involves the examination of the specimen through a cover-glass, and unless the glass is mounted, by means of Canada balsam, in optical contact with the metal surface the use of high-power immersion objectives is rendered impossible. The avoidance of cover-glasses is eminently desirable from the point of view of obtaining the best microscopic vision.

An alternative means of preserving specimens of most metals consists in immersing them in a bath of mineral oil or smearing them thickly with pure vaseline or other fatty substance. Care must be taken to ensure the freedom of the oil or grease used from all mineral and fatty acids, but if this precaution is taken, specimens will keep for a very long time when thus treated. Unfortunately the process of removing the oil or grease and cleaning the surface is somewhat troublesome, and after several repetitions the surface is apt to become increasingly scratched, so that repolishing becomes essential almost as soon as if a less perfect means of preventing corrosion had been used. In the case of iron and steel specimens, an alternative method consists in immersion in a strong solution of chromic acid. This renders the iron chemically "passive" and no corrosion occurs, while the chromic acid solution is easily washed away with water and alcohol. The specimen thus treated may then be freely exposed, since the passive state of the iron continues for some time, particularly if the surface is not scratched or rubbed.

For most laboratory purposes, where preservation of the specimens is only required for the time during which the particular investigation may last, it is usually found sufficient to store the prepared specimens, as mounted on their glass slips, in an ordinary large dessicator, such as is used by analytical chemists, the lower portion of the dessicator being filled with soda-lime. This maintains a dry atmosphere free from carbon dioxide in the dessicator, and if this is not opened too often, the specimens are thereby adequately protected from corrosion.

§ (5) Special Sections.—When it is necessary to prepare sections for microscopical examination from certain objects of special shape, difficulties are encountered which can only be overcome by special methods. The most frequent case of this kind arises when it is desired to examine the transverse section of a very thin object such as a thin sheet of metal or a fine wire. Such a section presents too small a surface to lend itself to grinding and polishing in the ordinary way. Not only is the object inconvenient to handle and liable to cut or otherwise damage the emery papers and polishing pads, but owing to the small area of contact it becomes extremely difficult to hold the specimen in a constant position and consequently the surface tends to become seriously rounded. In the case of sheet metal this difficulty can be overcome in a variety of ways. One simple method is to clamp a number of small pieces of the sheet to be sectioned tightly together by means of small bolts or rivets, and then to cut a section through the pile of pieces thus formed. If the material is very thin, it may be inconvenient to clamp together a sufficient number to make up a reasonable thickness, such as three millimetres. In that case it is preferable to clamp a few thicknesses of the thin sheet under examination between two thicker pieces of metal, using for these supports a material having about the same hardness as that under examination. The whole compound mass can then be ground and polished like a single piece of metal. In the etching process, however, difficulties may arise, partly from the fact that the supporting metal may interfere with etching by acting as an electrochemical protection—as when copper and steel are used together—or it may be found that the etching

solution penetrates between the layers of thin sheets and causes trouble in subsequent washing. Where this is the case the best remedy is to separate the pieces before etching, but this makes any subsequent repolishing very difficult, and also renders mounting and levelling very awkward.

In the case of thin wires, the difficulty can be overcome by drawing them through a fine hole in a small piece of metal of similar hardness, the hole being drilled so as to make the wire a tight fit at one end, but with the other end of the hole rather larger. Where the wire can safely be exposed to a temperature of 100° C., it may be embedded in a small mass of Wood's fusible alloy, but it must be borne in mind that this alloy does not readily "tin" the surface of other metals, so that a really good joint is not obtained.

Another case requiring very special treatment is that of a section in which the examination of the microstructure at one of the extreme edges of the specimen is necessary. This is the case where it is desired to study a transverse section of a fracture or a section at right angles to some surface feature which has been observed on a previously prepared specimen. For rougher purposes, embedding in fusible alloy may be employed, but where an accurate section of an edge is required, more refined methods must be employed. The device has therefore been used,[1] with great success, of first coating the original surface of the fracture or of the specimen with a deposit of electrolytic copper which can, by suitable means, be caused to make a perfect junction with steel or other metals. For this purpose, commencing with a perfectly clean surface, a very thin layer of copper is laid down on the specimen from an electrolytic bath in which a cyanide electrolyte is used. The specimen is then rapidly transferred to the ordinary acid bath and the deposit of copper thickened to the desired extent—a layer two or three millimetres thick is generally ample. The compound mass can then be cut, ground, and polished without the slightest risk of damage to the edge of the specimen which is protected by the copper, which not only places it beyond the reach of mechanical injury, but also prevents the rounding off which is apt to occur close to the edge of an ordinary specimen. Some little care is, however, required to prevent erosion if a steel specimen embedded in copper is under preparation. Owing to the softness of the copper a marked difference of level is liable to be developed, but by careful work, avoiding the use of soft polishing pads, this can be kept down so low that the slight lowering of the level of the steel which subsequently occurs during etching equalises the surfaces. A further precaution, however, is required. Some surface flow always occurs during polishing, and the actual boundary between the two metals—steel and copper, for instance—is apt to be blurred in this way, and must be cleared by subsequent etching. In that case, however, it is essential that the polishing should have been carried out in such a manner that there has been a tendency for the steel to flow over the copper rather than *vice versa*. The reason is that while a thin layer of steel is removed during etching, copper in contact with steel cannot be so removed. By the careful use of this method it has been possible to show, in section, minute surface irregularities whose dimensions are of the order of a wavelength of sodium light.[2]

[1] Rosenhain, *Roy. Soc. Proc.*, 1905, lxxiv.

§ (6) The Metallurgical Microscope.—The general theory and construction of the microscope are dealt with in the article[3] on the optics of the instrument, so that in the present connection it is only necessary to consider those matters in regard to which the metallurgical microscope differs from the more general forms of the instrument. These differences arise almost entirely from the fact that the specimens to be examined in metallurgical work are always opaque, and have therefore to be examined under reflected instead of transmitted light, while none the less the highest available resolving powers and magnifications are frequently required. It follows at once that the whole of the substage of the ordinary microscope is not required, being replaced by what is usually termed a "vertical illuminator," whereby light is thrown down upon the surface of the specimen through the objective itself. This form of illumination makes certain demands upon the mechanical construction of the instrument, and these are responsible for the differences which exist between the ordinary microscope and the more usual forms of metallurgical instrument. There is, however, a special type of metallurgical microscope which departs radically from the ordinary type, but it is at least doubtful whether the result is advantageous.

In view of their importance in regard to the design and construction of the metallurgical microscope, it is desirable, in the first instance, to consider the methods employed for the illumination of opaque metal specimens. Two modes of illumination are possible, at all events with the lower magnifications. The simplest is the employment of ordinary oblique lighting, such as is used for the examination of moderately large objects under low powers. Here a beam of light, derived from a suitably placed lamp, generally by the aid of a condenser, falls obliquely on the specimen.

[2] *Ibid.*

[3] See "Microscope, Optics of the," Vol. IV.

Sometimes the light is further concentrated on the surface under examination by means of a parabolic reflector carried on the microscope itself. This method of illumination is limited in its applicability by the fact that it requires an appreciable free-working distance between the objective of the microscope and the specimen. With lenses up to 8 mm. focal length this distance is reasonably sufficient, but for higher powers with lesser working distances the oblique beam must be thrown upon the specimen at so large an angle of incidence that it gives very little light and also serves for little beyond throwing into relief the imperfections of the surface. For visual purposes, therefore, oblique light cannot be usefully employed with magnifications much higher than 200 or 300 diameters, unless these are obtained with unduly low-power objectives of very low resolving power. Within this limitation, however, there can be no doubt as to the value of oblique light examination. It brings out, in the first place, the effect of " oriented lustre " described above, and serves generally to show the relief effects of the surface. Provided that care is taken to interpret the appearances correctly, it affords information as to what are pits or hollows and what are raised areas or mounds. For some of these purposes, however, a diffuse beam of oblique light from an ordinary lamp and condenser, and still less the wide-angle beam from a parabolic reflector, are entirely useless, since it is not easy to be sure from what direction any particular shadow may be thrown. An approximately parallel beam of light gives much less satisfactory effects so far as general appearances are concerned, but allows of exact interpretation. For this purpose, however, it is essential that the angle of incidence of the beam should be variable at will, at all events in the azimuth of the surface under examination. This can be secured in a crude manner by moving the source of light, but it is far more satisfactory to have the microscope equipped with a rotating stage, the rotation being so arranged that a complete revolution can be made, and that the axis of rotation can be made concentric with the optical axis of the microscope. These latter requirements are, of course, only met by instruments of the highest class. When a suitable etched specimen of metal is rotated under a unidirectional beam of oblique light, very striking effects are often observed, and these have formed the subject for an effective use of cinema-photography. For visual purposes the value of this method of examination can be further increased very considerably by employing simultaneously several unidirectional beams of oblique light brilliantly coloured by passing through suitable coloured glass or gelatine filters. By this means it is easy to demonstrate the nature of surface markings. Thus a ridge, as at (*a*) in *Fig.* 3, is readily distinguished from a step, such as that at (*b*) in the same figure. Rays of red light coming from the right, as at RR, strike the right-hand slopes of both (*a*) and (*b*), which thus appear as red bands ; on the other hand, green light coming from the left illuminates the left-hand slope of (*a*), as at G, but does not illuminate any portion of (*b*), and when the specimen is rotated through 180°, the reverse effect is obtained. Opportunities for the employment of oblique lighting on these lines frequently occur in metallurgical work, but unfortunately these methods have been somewhat neglected.

The method of " vertical " or, as it is more correctly termed " normal " illumination,

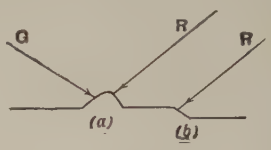

FIG. 3.

lending itself to use with all magnifications, and giving images which appear to be much clearer and simpler than those obtained with oblique light, is much more widely employed, and may be regarded as the usual method of illuminating metal specimens. This kind of lighting is obtained by placing behind the objective of the microscope, *i.e.* at some point between the objective and the eyepiece, some form of reflector. Many types of reflector are used, but in principle they resolve themselves into two kinds, viz. those which are more or less transparent and cover the entire aperture of the objective, and those which are opaque and cover only half or less than half of the objective opening. The two types are diagrammatically indicated in *Fig.* 4 (*a*) and (*b*). Type (*a*)—the transparent reflector—has the advantage that by its aid perfectly central illumination of the specimen can be achieved. On the other hand, of the light incident upon the reflector not more than about 15 per cent is reflected downward through the objective, while of the residue which is returned upward from the illuminated surface through the objective, another 15 per cent is reflected outward and lost to the image. A powerful source of light is therefore required in order to obtain a bright image with this type of illuminator, particularly where focussing for photographic purposes is necessary. This wasteful use of light has the disadvantage that scattered light, and undesirable reflections, tend to render the image slightly milky. There is the further difficulty that the rays forming the image have to pass through the

reflector. This is frequently made of extremely thin glass, such as that used for microscope cover-slips, and its very small thickness renders it relatively harmless from the optical point of view. For the very best work, however, a slight loss of definition due to this cause cannot be ignored.

Type (*b*)—the opaque half-field reflector—overcomes most of the disadvantages of type (*a*), but possesses two important limitations. In the first place, perfectly central illumination cannot be obtained, since at best the cone of rays emerging from the objective, to fall on the specimen, can come only from one-half of the objective. If there are minute differences of level on the etched surface, slight shadows may therefore be thrown. The existence and extent of these can, however, be readily ascertained by rotating the specimen under observation. As a rule there is no

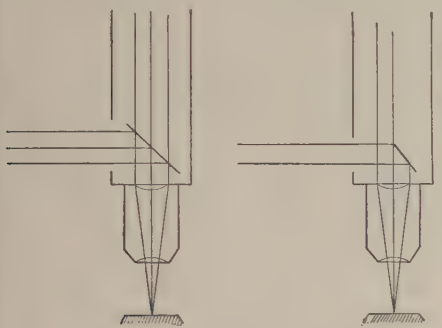

FIG. 4.

visible change in the image. In the second place, while the image-forming rays do not pass through any distorting medium, however thin, they are limited to a semicircular or D section. This has a very marked effect on the resolving power of the objective, since its effective aperture at right angles to the edge of the D is only one-half of its normal aperture. Where specimens are examined which exhibit fine laminated markings lying near the limit of resolution, the effect is exhibited in a striking manner if the specimen is rotated. When the laminations lie at right angles to the edge of the illuminator they are clearly resolved, but when placed parallel to that edge they merge into a slightly mottled patch. This is one of many instances in metallurgical work where the question of resolving power must be very carefully taken into account in the interpretation of observations.

The reflector, whether of the transparent or of the opaque half-field type, together with the fitting in which it is carried, is usually termed a "vertical illuminator." In its earlier and simpler forms such a fitting was intended for little more than a temporary means of adapting any ordinary microscope for use with vertical illumination and the examination of opaque sections. It consisted therefore of a short extension to be screwed on to the lower end of the body-tube of the microscope, between that tube and the objective. This form of fitting is still in extensive use, even with microscopes specially designed for metallurgical work. It is subject to several serious disadvantages: in the first place, it constitutes an additional joint in the body of the microscope and thus introduces an element of unsteadiness. This is particularly the case because in the majority of instances the illuminator fitting is made capable of rotation in order to allow it to be used with light coming from any desired direction. It will be seen that such a fitting adds an appreciable element to the difficulties of centring the objective and the rotating stage. A further disadvantage of the "screw-on" illuminator is that it lengthens the body-tube of the microscope, and may make it difficult to adjust the length of the optical requirements of the lenses used if these are designed for the short body-tube. Finally, such a fitting is necessarily small and comparatively light, with the result that, as a rule, no adjustment of any kind is provided beyond the mere power of rotating the reflector about its horizontal axis. The absence of facilities for moving the reflector in the plane at right angles to the optic axis so as to centre or otherwise adjust the illumination, and for raising or lowering the reflector along the optic axis of the microscope, proves a serious hindrance where the best kind of work is to be done. In some of the later instruments specially designed for metallurgical work, therefore, the illuminator has been constructed as an integral part of the microscope body-tube, or rather the reflector is inserted into the microscope in much the same way as various lenses and other fittings are inserted into the tube of a good petrological microscope. In this way the rapid interchange of various reflectors becomes possible without disturbing the focus or the field of view of the objective, and adequate adjusting movements for the reflector can be easily provided. The only disadvantage seems to lie in the fact that the illuminator can no longer be rotated, and that, therefore, the source of light must always be placed in one of three definite positions; in practice, however, this proves no source of inconvenience. This arrangement of illuminator forms an essential part of the special type of metallurgical microscope (Rosenhain microscope) described and illustrated below.

In all types of such illuminators the actual reflectors may be of various types. For the "transparent" type it is most usual to employ

a small micro-coverglass, as thin and flat a specimen being used as can be obtained. With a view to improving the definition obtained with this type of reflector, attempts have been made to use optically worked, plane-parallel pieces of thin glass, but it is doubtful whether the necessarily greater thickness of such plates does not outweigh the advantage of their more perfect surface. In order to increase the amount of light available for the image with this type of reflector, attempts have also been made to use reflectors which have been partially silvered or platinised in order to increase the proportion of reflected light to something like 50 per cent of the incident light. Increased brightness has been obtained in this way, but unfortunately the definition of the image and its crispness of contrast suffer very appreciably. Reflectors of the half-field, opaque type were first introduced by Zeiss, who still employs a small totally reflecting prism. This gives excellent results, but the bulk of the prism makes it unsuitable for use where considerable latitude of adjustment is desired. A semicircular slip of thin glass, well silvered on the back, gives very nearly as much light as the prism, and is lighter and occupies less space.

In regard to the production of satisfactory "normal" or "vertical" illumination, it is next necessary to consider the source of light and the optical system, if any, to be employed outside the microscope. A great variety of illuminants and optical systems have been used, but in regard to the majority of them it may be said at once that they fail to recognise some of the simplest fundamental principles which govern microscopic illumination. Thanks to the special conditions of work with normal illumination, it is possible to obtain the most satisfactory results by an extremely simple method, requiring no optical system whatever outside the microscope itself. This system is based upon a principle which has often been termed, somewhat loosely, that of "critical illumination"; it really depends upon the fact, well established by observation, even if its theoretical basis is not universally accepted, that extremely satisfactory illumination, allowing of the best utilisation of lenses of large numerical aperture, is obtained when a sharply focussed achromatic (or even apochromatic) image of a uniform source of light is thrown upon the surface under examination. When thus illuminated, the surface under examination may be regarded, for purposes of optical theory, as self-luminous; *i.e.* each point of the object radiates light waves having no necessary or regular phase relationship with the waves emanating from adjacent or other points.

With a vertical illuminator it is particularly easy to obtain such illumination, which may, perhaps, be termed "focussed lighting." Apart from the intervention of the field-lens of the eyepiece, the microscope objective forms a real image of the object, when in focus, near the upper end of the tube at a distance which is readily ascertained. If, at this distance from the objective, a luminous source is placed, the objective will form a small but very bright image of that source in sharp focus on the surface of the object (the metal specimen). Provided that the source has a uniformly illuminated surface as large as, or slightly larger than, the area occupied by the primary magnified image formed by the objective, then the whole area of the specimen corresponding to that image will be covered by the uniformly bright and sharp image of the source. It is, of course, obviously impossible to place the source of light in the actual back-focus of the objective, but if it is placed at one side, opposite the reflector of the vertical illuminator, and at a distance from that reflector equal to the distance from that reflector to the image formed by the objective at the eyepiece end of the instrument, the same optical conditions will be realised. The whole arrangement will be readily understood from the diagram of *Fig.* 5 (*a*), where I is the real magnified image

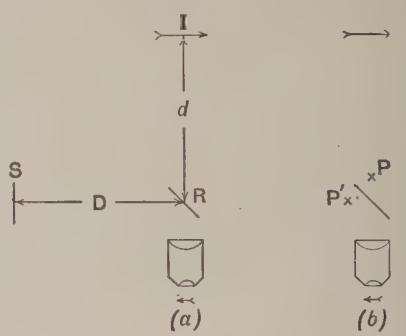

FIG. 5.

formed by the objective at a distance *d* from the reflector R, and S is the source of light placed at a distance D from R equal to *d*. The only conditions necessary for the successful use of this system of illumination are that S shall be placed at approximately the right distance, and that the source shall be sufficiently large and uniformly bright, while it must also be free from even minute detail which would otherwise be superposed on the image. Thus an incandescent gas mantle by itself, or an electric filament lamp, would be equally unsuitable. Either of these sources, however, is quite satisfactory if employed to illuminate a piece of thin opal glass, which

then becomes the acting source of light and must itself be placed at S. Ground glass, although it transmits more light, is not usually of sufficiently fine grain. The correct position of S is readily found by hand adjustment; a small temporary mark is made on the opal glass, for instance, and this is moved about until this mark appears sharply in focus at the same time as some light-coloured specimen of metal viewed through the eyepiece. The temporary mark can then be removed and the position of S marked or otherwise fixed. A convenient method is to mount the source of light in a suitable casing or "lamp" provided with a tube, an inch or so in diameter, along which the light passes to the illuminator aperture of the microscope. If this tube is made of such a length that S is in the right position when the end of the tube is just out of contact with the side of the microscope tube, the whole arrangement becomes extremely simple and easy to set up or to reset if disturbed. It will be seen that with this system there are no optical parts outside the microscope itself; the only additional fitting which is desirable is the provision of a stop, best in the form of an iris diaphragm at the illuminator aperture. The use of a stop at this point furnishes the most satisfactory method of "stopping down" for use with this system of focussed lighting. As a rule, the objective can be used with less stopping-down when this method of lighting is used than with other arrangements.

The only real limitation to the use of this type of illumination lies in the fact that it is not as yet possible to obtain very intense sources of light which are sufficiently large and uniform in brightness to be used in this manner. For all visual work the brightness of image obtainable with a thin opal shade lighted by a good incandescent lamp is amply adequate. For photography, however, and particularly for the accurate focussing of the image when high magnification and comparatively small aperture are employed, much more light is required. The tungsten-arc lamp (known as the "Pointolite" lamp) recently introduced affords a bright area of moderate size, but even the largest of these lamps are not yet large enough to be employed directly. This difficulty can be overcome to a certain extent by using in place of the actual source of light at S a magnified image of the source formed at S by means of a suitable optical system. In that case, however, the intensity of the source of light is considerably reduced, and the arrangement does not give sufficient light with the present types of "Pointolite" lamps.

Theoretically, an alternative method of illumination, which should also be satisfactory, would consist in placing a powerful point-source of light at a point P (*Fig.* 5 (*b*)), so related to the objective as to correspond to its equivalent principal focus. Neglecting the aberrations of the lens system when used in this way, the objective should then emit a beam of parallel light falling upon the surface of the specimen. Actually, the lens is not designed to give a parallel beam in such circumstances, nor can a point-source be used. What is done is to focus a sharp image of a very bright source of light upon a point P′ just outside the illuminator aperture and approximately at an equivalent distance to the point P. In this way a very large amount of light can be sent through the small illuminator aperture (usually restricted by an iris diaphragm), and this forms a very bright patch on the surface of the specimen. This form of lighting, however, is always more or less troublesome. With an arc lamp it requires somewhat elaborate condensing arrangements, while the heat-rays require to be absorbed by means of a suitable tank. The worst inconveniences arise from the fact that, owing to the exact focussing of the image of the arc on the illuminator aperture, any slight shift of the arc is apt to disturb the whole lighting arrangement. There is also some considerable difficulty in securing really uniform brightness over the whole field, and in avoiding the presence of coloured bands, arising from the fact that the large condensing lenses which form the image of the arc are usually non-achromatic. For visual purposes, however, these difficulties largely disappear, since it is sufficient to focus the image of even a small oil-lamp upon the illuminator aperture by means of a small achromatic stand-condenser to obtain reasonably good lighting.

In connection with vertical illumination, mention may be made of some further special devices. Some of these serve to embody the entire illuminating apparatus with the microscope itself. This has been done, for instance, in a simple form of workshop metallurgical microscope designed by Stead, in which a minute electric-lamp bulb is attached to the microscope opposite the reflector of the illuminator. A more elaborate device of the same kind, in which a special system of condensing lenses is included, is the Watson-Conrady illuminator. A more original device is one recently put forward in America. Here the illumination is, strictly speaking, oblique in the sense that the light does not pass through the objective before reaching the specimen. The source of light, however, is a very small annular electric filament lamp placed immediately surrounding the objective. This lamp throws a cone of convergent light upon the surface of the specimen, and this illumination, with objectives of moderate power, yields effects very

similar to those obtained with true normal lighting.

The method of illumination employed in the examination of metal specimens is, in the main, the determining factor upon which rest all the essential differences between an ordinary microscope such as that used for biological or bacteriological work and one designed specially for metallurgical purposes. In the former type of instrument the light enters the optical system of the microscope through the aperture of the sub-stage, and this aperture is, approximately, kept in a fixed position, all focussing movements being carried out by means of movements of the body-tube. In the metallurgical microscope, on the other hand, the light enters through the aperture of the illuminator, and—whatever system of lighting may be adopted—it becomes important that this aperture should remain approximately fixed, since otherwise the whole external lighting system would require readjustment for every considerable change of focus, such as that arising from the use of a different objective or of a thicker or thinner specimen. The result is that all modern metallurgical microscopes are constructed with a movable stage whereby at least the rougher focussing can be carried out. In most instruments both coarse and fine focussing adjustments are still retained for the body-tube, but the coarse adjustment at least is entirely unnecessary, and even the fine can be quite well omitted. The movable or focussing stage has the further advantage, particularly in those types of instrument in which the illuminator is a fitting screwed to the lower end of the body-tube, of allowing a very large distance, when needed, between stage and objective, thus permitting either the use of very long-focus objectives or of thick specimens.

The simpler forms of metallurgical microscope closely resemble the corresponding grades of ordinary microscopes, with the difference that the stage usually has a solid platform, and is capable of being raised or lowered by a rack-work motion which serves for coarse focussing. Some of the more elaborate stands also follow closely upon the ordinary models, except for the movable stage and the absence of sub-stage illuminating appliances. A much more radical departure from conventional design has been made in the Rosenhain[1] metallurgical microscope, which is illustrated in *Fig.* 6. The general design of this instrument, with its wide triangular base and the girder-shaped limb, recalls a machine-tool rather than an ordinary microscope. Extreme rigidity is aimed at in this instrument, and, accordingly, the wide body-tube is rigidly attached to the limb, all focussing movements, both fine and coarse, being relegated to the stage. This arrangement is facilitated by the fact that no sub-stage illumination is needed, so that it is possible to mount the fine-adjustment slide and screws in or close to the optic axis of the microscope. This arrangement entirely avoids any "overhang" as regards the fine-adjustment slides, and eliminates a certain amount of lateral displacement of the image, which in most microscopes is apt to occur during fine-adjustment focussing under extreme magnifications. Rigidity is further secured by the abolition of the screwed-on illuminator, in the manner already indicated. The stage is further provided with means for complete rotation about the optic axis, and the use of oblique light is facilitated by leaving the surface of the stage completely free, the milled heads actuating the mechanical motion being placed below instead of above the stage.

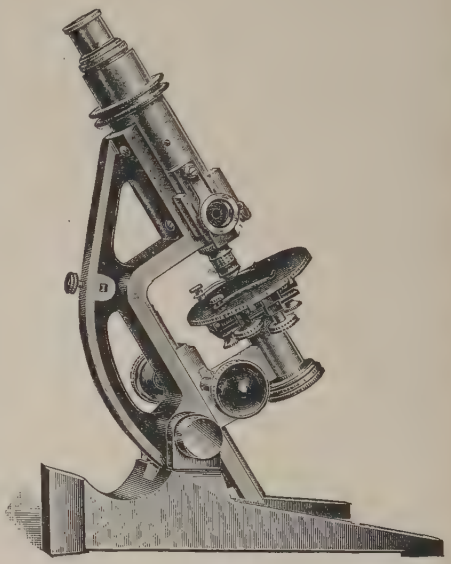

FIG. 6.

A number of designs of metallurgical microscopes, usually provided with a photomicrographic camera, have been based upon a type originally put forward by Le Chatelier.[2] Here the stage forms the highest part of the instrument, and the specimen is placed face downward over an aperture. The inverted specimen is then examined by means of an ordinary microscope objective pointing upwards. Immediately below the objective is the illuminator prism, and below this again is a reflector, which may be either a totally reflecting prism or a carefully worked metallic plane mirror, which throws

[1] Rosenhain, *Roy. Microscopical Soc. J.*, 1906.

[2] Le Chatelier, *Étude des Alliages*, 1901, 421.

the image formed by the objective to one side into a horizontal tube fitted with the usual eyepiece. Focussing, both coarse and fine, is done entirely by means of the stage. In the original Le Chatelier model, the camera was placed in the base of the instrument; when the reflector, which usually serves to throw the light into the eyepiece tube, was withdrawn, the rays coming from the objective were allowed to travel straight downwards, coming to a focus upon a suitable screen or on a photographic plate. This arrangement, however, implied the use of the objectives, for photographic purposes, without the aid of any eyepieces, and this proved inconvenient in view of the fact that the apochromatic objectives do not yield their best results unless used in conjunction with the proper compensating eyepieces, and also because, in order to secure adequate magnifications, extremely large camera lengths are required. In more recent models, by Leitz and by Reichert, the tube first used for visual purposes has been connected to a horizontal camera, while for visual purposes a second horizontal tube is employed, so arranged that, by pushing another reflector into the path of the rays, they are again reflected at right angles into the eyepiece. The whole arrangement is indicated diagrammatically in *Fig.* 7, where *a*

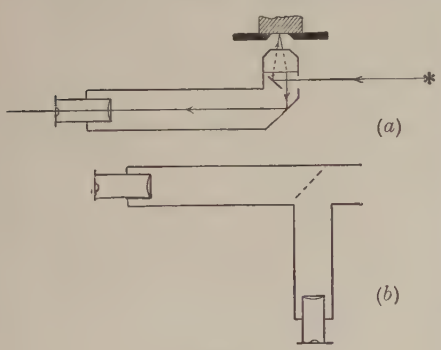

FIG. 7.

is a sketch elevation showing the paths of the image-forming rays, while *b* indicates the relation of the visual to the photographic tube.

The advantages claimed for the Le Chatelier type of inverted metallurgical microscope are that it obviates the necessity of mounting the specimen at right angles to the optic axis of the instrument, and that it allows of visual examination and photography of a specimen without shifting it or the instrument. The former point has already been discussed. With regard to the latter, it must be pointed out that with an instrument of this kind visual examination is rendered comparatively irksome and difficult. A horizontal eyepiece is not conducive to comfort in prolonged observation, while the relative situation of the eyepiece and the focussing and stage-movement screws renders the observer's attitude strained and awkward. The whole design of the instrument suggests, in fact, that really prolonged and careful visual study of specimens was not contemplated, and yet it is this, rather than great facility in obtaining photographs, which is really most important. The inverted microscope has the further disadvantage that the crispness and definition of the images are certainly not improved by the additional reflection to which they are subjected, while, finally, the movement of the stage takes place on slides which are necessarily considerably away from the optic axis of the instrument, so that lack of rigidity makes itself evident. While very excellent work has undoubtedly been done with instruments of this type, they show no tendency to displace the more usual forms in English practice.

In addition to what may be termed the regular microscope as employed for the study of metal specimens under all magnifications, up to the highest usefully available, some auxiliary types of microscope find useful application in metallurgical work. The most important of these is the stereoscopic binocular microscope of the Greenhough type, first made by Zeiss. This instrument consists, briefly, of two separate optical systems focussed upon the same field of view, the principle of the prism binocular being used to secure adequate separation of the eyepieces and, incidentally, to erect the image. Twin pairs of objectives are used, and magnifications up to 80 diameters are obtainable. For metallurgical purposes this instrument is particularly useful in the examination of fractures, and of such objects as the surfaces of solidified ingots, etc., where considerable differences of level exist. These are brought out in brilliant distinctness by the stereoscopic effect obtained with this microscope. For polished and etched specimens, on the other hand, this type of instrument has no advantages. The same remark applies also to the large and elaborate binocular instruments working with a single objective; the differences of level met with in properly prepared sections do not lend themselves to observation in this way.

While metallurgical work frequently makes demands upon the highest resolving power and correspondingly high magnifications which the modern microscope can yield, other aspects of the work often call for facilities for the production of photographs at quite moderate magnifications, such as from 2 to 10 diameters. Such low magnifications, up to about 30 diameters, are not readily obtainable with the ordinary types of microscope and objective. Special lenses, such as the Zeiss

series, have been produced for this purpose, and meet the requirements up to a certain point very well. These lenses are not of the type of microscope objectives, but are in reality small short-focus photographic objectives, specially designed to work at positive magnifications. They can be used either in an ordinary camera suitably mounted, preferably in a vertical position, or in any microscope having a sufficiently wide body-tube. For magnifications below 10 diameters, however, the existing series of lenses are not well suited, and there is the further difficulty of securing uniform illumination over the large field covered at such low magnifications, combined with sufficient brightness to allow of easy focussing. A special outfit—or a set of appliances suitable for adapting an ordinary outfit for work of this kind—would meet a very real need of the metallurgist. In this connection a good deal has been heard recently of devices in which a low-power, long-focus objective is employed, and the relatively very slightly enlarged image produced by this lens is then magnified by a powerful compound microscope. Photographs having quite an effective appearance can be produced with such an appliance, and special claims are made for the great depth of focus obtained. This is of course the result of the circumstance that such a system has an extremely low angular aperture, since it is on angular aperture alone that "depth of focus" depends. Such a system, however, is merely an elaborate equivalent to the use of a combination which is well known to be unsatisfactory in microscopic work, viz. a low-power objective with a high-power eyepiece. Its use for metallurgical purposes is not to be advocated.

The choice of objectives for metallurgical work generally must be governed by much the same considerations as those which govern the same choice in other branches of microscopy. The question of resolving power is of very great importance, so that it becomes very important to obtain magnification by means of a high-power, wide-angle objective rather than by subsequent magnification of the image by means of an eyepiece or by projection. For the best work there can be no doubt that apochromatic objectives of the highest grade are needed, and even the greatest resolving powers obtainable with immersion objectives of that class are often insufficient for some of the most interesting structures. In practice a set of objectives consisting of 16 m/m., 8 m/m., 4 m/m., and 2 m/m. or 3 m/m. objectives, the last named with a numerical aperture of at least 1·25, and preferably 1·40, are found very useful, together with a set of compensating eyepieces, and, for photographic purposes, one or two special projection eyepieces. Good work, although not of the very highest class, can also be done with less costly lenses of a good achromatic series, particularly if the light employed is kept approximately monochromatic by the use of suitable light filters, which are now readily obtainable. For all lenses intended for metallurgical work, however, two special requirements should be considered. The first is that the objects viewed are, in almost every instance, uncovered, so that lenses corrected for use with cover-glasses should not be employed, nor is the provision of the expensive and somewhat cumbersome correction collar required for this kind of work.

The second special requirement for metallurgical microscope objectives arises from the fact that the objective is usually employed as its own condenser, and therefore has to transmit the incident light as well as that proceeding from the object to the image. Here the difficulty arises from the fact that a portion of the incident light is reflected back by the surfaces of the lenses of which the objective is built up, and this reflected light, passing up the tube of the microscope, renders the image "milky" and weak. This is, perhaps, the most serious difficulty which confronts the metallurgical microscopist who has not a set of specially constructed objectives at his command. In such special lenses provision is made for stopping this internally reflected light by mounting the whole objective in a short mount, so that the rear surface of the objective lens comes well into the lower end of the microscope tube itself instead of lying some way down in the lens mount. This position of the rear surface is important, because it makes it possible to bring the reflector of the half-field illuminator close down against the rear surface of the lens. In this position the reflector itself catches and stops most of the light which is thrown back by the objective, since by far the greatest part of this light is that reflected from the rear surface itself. This stopping effect of the opaque reflector constitutes one of its greatest advantages over the transparent reflector, but it can only be utilised to the full if not only the position but also the curvature of the rear surface of the objective is suitably designed. The best effect is obtained when this rear surface is either plane or only very slightly curved, and this is an important condition for the satisfactory performance of a microscope objective working with a "vertical" illuminator.

As in other branches of microscopy, the limitations of resolving power encountered in lenses working with ordinary light have led to an endeavour to obtain increased resolution by means of light of shorter wave-length. While for work with transmitted illumination

on suitable subjects the use of ultra-violet light, working with quartz or silica lenses, has proved successful, in metallurgical work the difficulties are much greater and have not yet been surmounted. These arise mainly from the fact that the beam of ultra-violet light intended to illuminate the specimen must first enter the microscope tube and be reflected down through the objective. Unfortunately, the ultra-violet light, which is inevitably reflected and scattered internally in this process, produces vigorous fluorescence both in the lenses of the objective and in other parts of the instrument. The result is serious fogging of the photographic plate by which alone the ultra-violet images can be adequately rendered visible. Where moderate magnifications are used, the intensity of the image itself can be kept high enough to give a reasonably good result in spite of the stray light; but for the highest magnifications — where alone the use of ultra-violet light is really important—it becomes almost impossible to obtain a clear image.

Reference has already been made, at various points in the discussion of the metallurgical microscope, to methods adopted in connection with the photomicrography of metals. The methods employed do not differ appreciably from those used in other branches of photomicrography, although certain modifications are necessarily introduced in consequence of the use of the vertical illuminator. The most important consequence is that the illuminating system cannot be conveniently placed in the prolongation of the optic axis of the microscope, but is either placed in a line passing through the illuminator and at right angles to the optic axis of the instrument, or parallel to that axis, but slightly at one side, in such a way that the beam of incident light can be thrown into the illuminator aperture by a single reflection from a suitably placed mirror or prism.

As has been indicated above, powerful sources of light are desirable in order to facilitate exact focussing, and either the electric carbon arc or the tungsten arc (Pointolite) are employed, although the "limelight," or other powerful sources of light, can also be used. The intensity of the light employed must of course largely determine the length of exposure required in taking a given photograph, but it is desirable, except in very favourable circumstances, to reduce the exposure as much as possible, particularly with high magnifications, since slight mechanical disturbances, or even changes of dimensions of the apparatus arising from gradual changes of temperature, are liable to spoil a photograph which has been taken with a long exposure. On the other hand, the character of the images to be photographed in most examples of metallurgical work is such as to render desirable the use of "process" photographic plates. These plates are "slow," and thus tend to lengthen exposure, and therefore furnish another reason for the use of a powerful illuminant. Much of the best photomicrographic work on metals has been done with apparatus in which the source of light is an arc lamp working with carbons at right-angles to one another and carrying a current of 25 to 35 amperes at a voltage of 65.

As a rule the appearance of a metallic section can be fairly well represented by a monochrome photograph, since distinctions of colour are not usually very vivid, although in visual observation much importance must be attached to slight variations of shade and tint. Heat-tinted specimens, however, and others etched in special ways, furnish displays of brilliant colour, while striking effects can also be obtained by multicoloured oblique illumination (see above). These can be satisfactorily recorded by means of the modern processes of direct photography in natural colour, such as the Lumière autochrome process. Considerable care and experience are, however, needed to obtain true representations. Particular attention must be paid to the use of a suitable light filter with the electric arc; failing this, the blue colour of the arc light is translated by the colour-sensitive plate into an unduly blue shade pervading the whole photograph.

Opportunities for the useful application of the cinematograph to metallurgical microscopy are also somewhat rare. Actual movement does not of course occur, except when the specimen is intentionally moved by means of the stage. In some cases, however, simple rotation of a specimen gives rise to a series of changing effects which cannot be conveyed by a single photograph or even by a series of such photographs. Such an effect is obtained when a well-etched section of a pure metal, exhibiting the typical oriented lustre, is rotated under oblique light. A specimen showing slip-bands (see article on "Metals, The Relations of Strain and Structure") shows still more striking effects when moved in this way. Both these effects have been successfully recorded by means of the cinematograph. Gradually changing effects can also be obtained, either by the progressive etching action of a "slow" reagent (see above) or by the application of gradually increasing strain, and these changes can be shown by the cinematograph. In this type of case particularly, however, there is no need for a large number of rapidly made exposures. All that is required is to take a few exposures at intervals so arranged as to show only slight changes at each step. Another method of showing the successive effects of increasing strain on the screen by the cinemato-

graph is to prepare a specimen of such a shape that it exhibits all the stages of strain, from the beginning of plastic deformation up to the severest stage prior to rupture, successively along its length. If such a specimen is passed under the microscope slowly while cinematographic photographs are taken, the surface, with its changing features, can afterwards be shown on the screen, apparently flowing past the spectator at a considerable speed. In taking such a series of photomicrographs on the film of an ordinary cinematograph camera, however, there is considerable difficulty in securing that the image shall remain in adequate focus while the specimen is moved. This can be best secured by introducing a transparent reflector into the path of the rays forming the image, and thus forming a faint reflected image in a suitably placed eyepiece at one side. Provided that the focus on the film and in the side eyepiece have previously been carefully registered, this device enables an observer at the side tube to keep the image in focus while the specimen is traversed and the film exposures are made.

Note.—A large amount of specialised information on metallurgical microscopy is contained in the *Trans. Faraday Soc.*, Sept. 1920, xvi. part i.: "The Microscope—its Design, Construction, and Applications: a Symposium and General Discussion."

W. R.

METALS, THE RELATIONS OF STRAIN AND STRUCTURE — AMORPHOUS METAL

§ (1) Plastic Deformation of a Pure Metal.—In the present article it is proposed to consider, in the light of modern knowledge of the internal structure and constitution of metals and alloys, the manner in which these materials undergo plastic or permanent deformation and fracture. It will be convenient, in the first place, to confine our attention to pure metals or to alloys which consist solely of crystals of one constituent (solid solutions), afterwards endeavouring to extend the conclusions arrived at, as far as possible, to include the more complicated conditions which exist in duplex and other alloys.

A pure metal is now known to be built up of a large number of crystals of varying size and orientation, together forming what is known as a "crystal aggregate." When examined in the condition which is the result of fairly slow cooling from a high temperature, whether during the first cooling from solidification or after some annealing process, the crystals of such an aggregate are, as a rule, of approximately equal dimensions in all directions. Except near the edges of castings which have cooled rather rapidly, there is no direction of prevailing greatest length, and such a structure is often described as "equi-axed."

The question with which we are here primarily concerned is what change does this equi-axed crystalline structure undergo when the metal is subjected to plastic deformation, and what is the mechanism by which this change takes place? The first part of this question is easily answered by examining the micro-structure of a piece of a pure metal which has undergone some appreciable amount of plastic deformation, such as extension by cold-drawing or cold-rolling, or even by the pull of a testing-machine. A section cut parallel to the direction of extension shows that the metal still consists of an aggregate of grains, but instead of a system of equi-axed crystals we now find grains elongated in the direction of extension. These grains are obviously the deformed equivalents of the previously equi-axed crystals, and, since they appear after etching, in much the same manner as the undeformed crystals, they must possess at least some of the properties of crystals. Further examination confirms the crystalline character of these deformed grains; seen under oblique light, they exhibit the "oriented lustre" typical of etched crystalline surfaces in much the same manner as the undeformed grains, while deeper etching frequently reveals etching-figures which show no departure from uniform orientation throughout each elongated grain. It would therefore appear that the individual crystals of which a simple metal is built up can be deformed or elongated without losing at all events some of the most typical crystalline characters.

The manner in which such deformation of a crystal can occur is readily understood when it is realised that in any crystal which is built up by the arrangement of atoms (or molecules) on some regular space-lattice there must be certain planes upon which displacement can take place — from the geometrical point of view — without any disarrangement of the atomic distribution. From the geometrical point of view, this could occur on every plane parallel to two of the main lines of the space-lattice, and—provided that the displacement occurred in steps which are equal to or are exact multiples of the atomic spacing in the direction of displacement—such displacement or slip might leave the entire crystalline arrangement unchanged, although the external shape of the crystal would be altered. By numerous displacements of this kind, however, a very large degree of deformation of the crystal as a whole could be brought about. In the majority of mineral crystals with

which we are acquainted, such displacement is not ordinarily possible, because the material is "brittle," *i.e.* any small displacement along one of the crystal planes leads to rupture or cleavage. It is interesting to note in this connection that such brittle crystals are in the great majority of cases crystals of chemical compounds, and not of pure or nearly pure elements, while in simple metals we have to deal with crystals of elementary bodies. In these metallic crystals, it appears to be possible for displacement by slip to occur without rupture of the whole structure; in the case of intermetallic compounds, however, the typical brittleness of compound crystals is again encountered, even where the two constituent metals are themselves very ductile.

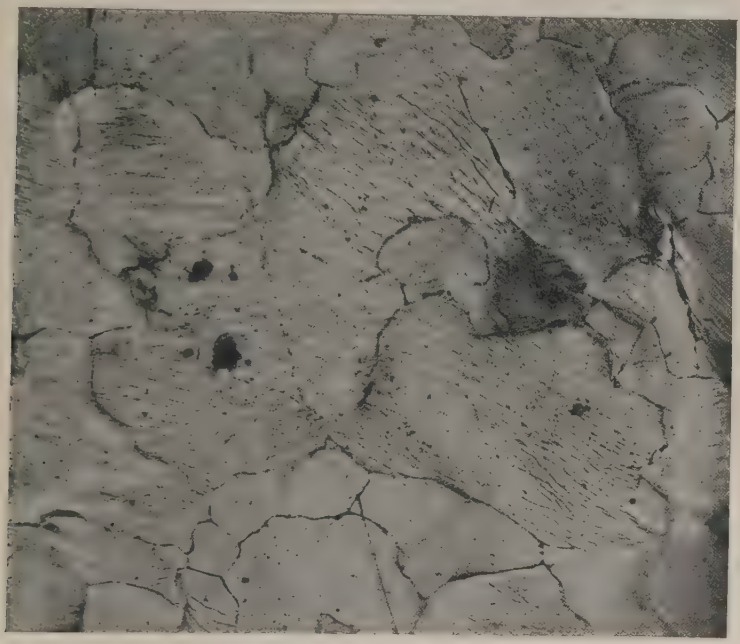

FIG. 1.—Slip-bands in nearly Pure Iron. ×300.

(i.) *Slip-bands.*—The occurrence of slip within the crystals of a metal undergoing plastic deformation is readily demonstrated by means of the microscope. If a strip of a pure metal be polished and etched, it presents the familiar polyhedral structure, similar to that illustrated in *Fig.* 1 of the article on "Metals and Alloys, The Microstructure of." If the strip thus prepared be now submitted to plastic deformation—for instance, by straining it in tension—the previously light and featureless surfaces of the crystals become covered with fine lines, at first few in number but, upon further straining, increasing until the entire surfaces of the crystals are closely cross-hatched. The appearance of these lines, as seen in iron and lead respectively, is illustrated in *Figs.* 1 and 2 respectively under a magnification of 300 and 150 diameters. Closer study of these lines confirms the view that they are due to the formation on the surfaces of the crystals of minute steps resulting from the occurrence of slip within the crystals. The optical properties of such steps are indicated in the diagram, *Fig.* 3, which shows the steps considerably exaggerated in relation to a microscope objective, while the paths of rays of light are indicated by the lines marked with arrows. Under "vertical" or normal illumination, the light falling upon the surface of the specimen from the objective of the microscope is reflected back by the bright horizontal surface of the crystal lying between adjacent steps. The light which strikes the steps themselves, however, is reflected outwards and does not enter the objective, with the result that the steps appear as black bands on a bright background, as indicated in the lower portion of the diagram. If, however, the incident light falls upon the specimen obliquely from one side, rays striking the flat horizontal portions of the crystal are reflected obliquely and pass outside the objective; rays which, coming from a suitable direction, strike the sloping steps, however,

are reflected upward into the objective, with the result that under such oblique illumination the steps appear as bright bands on a dark background. Further, under such illumination, only those particular steps will shine out brightly which happen to face the direction of the incident light. If either the specimen or the light be rotated, then successive sets of differently oriented steps will shine out as they come into the favourable position.

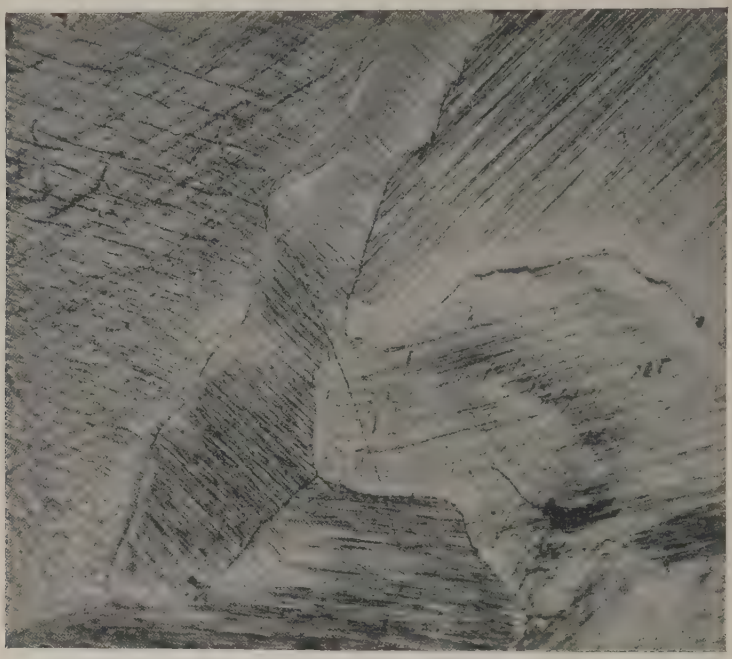

FIG. 2.—Slip-bands in Lead. ×150.

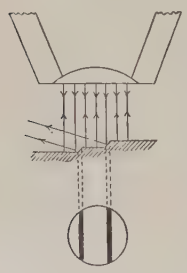

FIG. 3.

Observation confirms all these features in complete detail, so that little doubt is left, on this ground alone, as to the true nature of these lines. This nature is indicated in a rough diagrammatic manner in *Fig.* 4, where (*a*) represents a vertical section through the surface of a specimen at the junction of two adjacent crystals, whose boundary (in section) is shown by the irregular sloping line, while their cleavage or gliding planes are shown by dotted lines. At the surface there is a slight difference of level between the two crystals, which is the result of the differential attack of the etching reagent. The same region, after deformation and slip have occurred, is shown in the diagram (*b*) of the figure, which requires no further explanation.

That the diagram of *Fig.* 4 (*b*), however roughly, yet correctly, represents the section of a previously polished and strained specimen of a simple metal has received the fullest possible demonstration by the examination of an actual cross-section of such a surface. The metal used was a pure variety of iron (very mild steel), and, after straining, the surface on which the lines, or "slip-bands," as they are called, had been produced was coated with a fairly thick layer of electro-

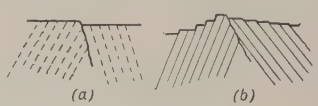

FIG. 4.

deposited copper. A section at right angles to the original surface was then cut and polished by special means, which made it possible to obtain a clean line of junction between the iron and the copper, thus giving an exact section of the original surface. On this section the steps due to the presence of slip-bands can be clearly recognised. A

photomicrograph of such a section, under a magnification of 1000 diameters, is reproduced in *Fig.* 5.

Besides the formation of slip-bands, plastic deformation of metals brings about certain other modifications of their micro-structure. True slip-bands, it must be borne in mind, are produced only when plastic strain is applied to a specimen of metal on which a properly polished surface has previously been prepared. If the specimen is polished (with or without etching) after the deformation has taken place, actual slip-bands cannot be seen. Even if a surface on which slip-bands have already been formed is repolished and etched, the bands do not reappear. The only exception to this rule is that when deformation has been pushed very far, so that the slip-bands are either very deep and strongly marked or occur in heavily marked groups, then on repolishing and etching lines are formed whose position corresponds to these intense bands. This phenomenon is only found in cases where metal has undergone very heavy cold-working, such as cold-rolling or wire-drawing, and is particularly noticeable in some of the copper alloys. It is probable, in fact, that the well-known etch-lines forming a species of "herring-bone" pattern on the crystals of certain wrought-copper alloys are really traces of previous intense slip.

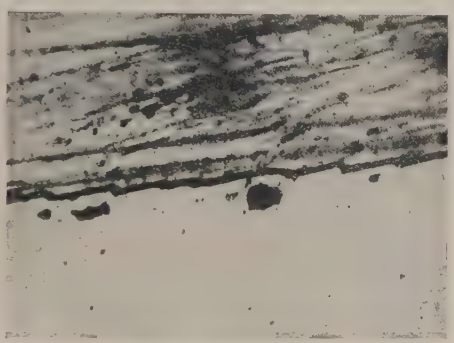

FIG. 5.—Slip-bands in Cross-section. ×1000.

It will, further, be obvious that when individual crystals undergo change of shape by slip, movement must also occur at the crystal boundaries, and this movement becomes distinctly visible if plastic strain is applied to a piece of metal on which a surface has been polished but not etched. The crystal boundaries become clearly outlined by differences of level so soon as the slip-bands begin to appear in the crystals. At high temperatures it has been shown[1] that the bulk of the deformation takes place by movement in the crystal boundaries, which are then much weaker than the crystals. In most metals at the ordinary temperature, however, the movement at crystal boundaries is relatively small.

(ii.) *Twinning.*—A further feature associated with plastic strain in many metals is the occurrence or formation of "twinned" crystals. The nature of crystalline twinning has been thoroughly studied and elucidated by mineralogists, who meet with the phenomenon in a great many minerals. It may be briefly described as a swinging over of the entire crystalline orientation through a definite angle. Twinning may occur on various of the principal planes of a crystal, and the "twinned" and normal parts of the crystal are then related to one another, as regards orientation, like an object and its mirror image. Metallic crystals formed by solidification from the molten state do not exhibit twinning, but in many metals it is extremely common after the material has been wrought and annealed, *i.e.* in crystals which have been formed by recrystallisation in the solid after previous plastic deformation. It is probable that the "swinging over" actually occurs during the application of plastic strain, and that deformation by twinning often accompanies deformation by simple slip. It is particularly frequent in copper and its alloys, and also in silver. On the other hand, iron at ordinary temperatures and aluminium do not exhibit it at all. Iron at high temperatures (γ-iron), however, exhibits it freely. The process of twinning is, however, entirely different in mechanism and in its effect from real slip. Twinning does not, for instance, produce minute steps in a previously-polished surface, and its presence can only be revealed indirectly, *i.e.* either by subsequent etching or by the peculiar manner in which slip-bands follow the changes of orientation in passing through a twinned band. Etching readily reveals even the slightest amount of twinning, while it does not reveal previously formed slip-bands (see above). There is, further, some evidence to show that twinning is not associated with any increase in the hardness of the metal, nor with any change of volume.

(iii.) *Neumann Bands.*—Although, as has been said above, twinning in the ordinary sense does not occur in iron at the ordinary temperature (α-iron), a phenomenon is met with when iron or very mild steel is subjected to severe shock or impact which may be of a somewhat similar nature. This is the formation of the features known as "Neumann Lines" or "Neumann Lamellae." When a

[1] Rosenhain and Humfrey, *Iron and Steel Inst. J.*, 1913, i.

previously notched bar of wrought-iron or mild steel is broken by a sharp blow, or if the surface of such metal is indented by a sharp blow struck, for instance, upon a small steel ball lying in contact with the specimen, these lines are found in profusion. They are observed when a section through the affected piece of metal is subsequently cut, polished, and etched. Like ordinary twinned bands, etching is required in order to reveal them; but, unlike ordinary twin bands, the Neumann lines are always quite narrow. They run, sometimes slightly stepped, across a crystal; sometimes there may be a number of such lines in one crystal, but their direction always changes, with the changing crystalline orientation, from one crystal to another. Their presence constitutes conclusive evidence that the specimen has been subjected to shock, but beyond this their true nature and mechanism have not yet been established. It has, however, been shown that where they occur the "hardness number" obtained by means of the Brinell ball impression is different, according as the impression is made by steady pressure or by impact; while in metals where Neumann lines are not formed, the figures obtained by impact and by steady pressure are in close correspondence. A similar discrepancy appears to exist in the results of what are known as "notched-bar impact tests," where the results found in iron or mild steel, consisting largely of ferrite, show considerable divergences from corresponding tests made on harder steels in which free ferrite plays a minor part. The tendency of ferrite to develop Neumann lines is probably associated with these differences, but further research on the point is required. While therefore the occurrence of twinning and of Neumann lines is a matter of very great interest and importance, it is probably safe to regard them as entirely secondary phenomena associated with the fundamental mechanism of plastic deformation by internal slip within the crystals.

The true character of slip-bands and the mechanism of plastic deformation by slip being accepted as well-established fact, the question arises whether slip alone can or does account for all the phenomena which accompany plastic deformation in metals. An answer in the affirmative can, in the writer's opinion, be given only in regard to very small amounts of plastic deformation. Where severe deformation is concerned there appears to be no escape from the view that other actions come into play, resulting in the partial destruction of the crystalline structure of the metal. The view that plastic deformation of metals results in the partial destruction of their crystalline structure, with the formation of an amorphous phase of the metal, was first put forward by Beilby,[1] and has since proved extremely fruitful.

(iv.) *Hardening.*—Perhaps the most striking phenomenon connected with the plastic deformation of metals is the effect which it produces upon their mechanical properties. This effect is, broadly, a hardening which results in a rise particularly in the elastic limit of the material when tested in the same direction as that in which it was previously deformed. Thus, by successive applications of tensile stress causing deformation (but not fracture) the elastic limit (limit of proportionality) of a piece of steel can be raised up to the breaking stress, while this breaking stress itself can be raised far beyond its original value. This apparent gain in strength of a strain-hardened (cold-worked) material is, however, apparent rather than real. In the first place, it is obtained at the expense of ductility, which decreases and finally disappears entirely. Further, the rise in the elastic limit in tension is, to a certain extent, counterbalanced by a fall in the elastic limit in compression, with the result that the total elastic range of the material is not very much increased by cold work. This feature is of particular importance where strain-hardened metal is intended for use under repetition (fatigue) stresses. Finally, material which has been very severely strain-hardened is apt to be unreliable from two causes: the strain may have been too severe locally, and thus have caused actual fracture, possibly internal, and at the same time such material frequently carries heavy internal stresses arising from unequal deformation of different parts, and these are liable to result in subsequent fracture.

Quite apart from any question of the practical reliability or usefulness of the additional "strength" imparted to metal by cold-working, this effect of strain requires full explanation by any theory which is put forward to account for the phenomena of plastic deformation. The explanation originally put forward by Ewing and Rosenhain,[2] and subsequently adopted by Tammann, was based on the idea that the very occurrence of slip-bands, *i.e.* of finite slip at relatively large intervals in the crystal instead of homogeneous slip or shear at every plane of the space-lattice,

[1] Beilby, *British Association Report, Glasgow*, 1901; "Surface Flow in Crystalline Solids," *Roy. Soc. Proc.*, May 1903, lxxii.; "The Surface Structure of Solids," *Journ. Soc. Chem. Ind.*, Nov. 1903; "The Hard and Soft States in Metals," *Phil. Mag.*, Aug. 1904; "The Influence of Phase Changes on the Tenacity of Ductile Metals," *Roy. Soc. Proc.*, 1905, lxxvi. A, 462; "The Hard and Soft States in Ductile Metals," *Roy. Soc. Proc.*, 1907, lxxix. A; "Surface Flow in Calcite," *Roy. Soc. Proc.*, 1909, lxxxii. A; "The Hard and Soft State in Metals," *Inst. of Metals J.*, 1911, No. 2, vi.

[2] Ewing and Rosenhain, "The Crystalline Structure of Metals," *Roy. Soc. Phil. Trans.*, 1900, p. 353.

implied that certain of the planes must show a lesser resistance to slip than others. These planes of easiest slip, however, would be exhausted during the first application of strain, and they would, moreover, be displaced and stepped in all directions by the simultaneous gliding which occurs on at least three sets of planes in each deformed crystal. Consequently, any further strain could only be brought about by a stress considerably higher than that which was needed to bring about slip in the virgin crystal. There can be no doubt that some such action occurs during plastic deformation, but it is difficult in the light of fuller study of the phenomena to regard this as a satisfactory explanation of all that occurs in strain-hardening. Thus, while the theory of selected planes may perhaps account for a rise in the elastic limit, it can scarcely account for an increase in the breaking stress. Nor can this explanation account for the changes of density—slight but perfectly definite—which accompany plastic deformation. Tammann, it is true, suggests that the slight decrease of density arises from the formation of minute interstices where the displaced crystal layers no longer fit in with one another at the crystal boundaries. This view, however, would suggest that in strain-hardened metal the grain boundaries are relatively weak, while in fact they are stronger than the crystals themselves.

(v.) *Beilby's Explanation.*—Beilby's theory of the formation of an amorphous phase, on the other hand, affords a much fuller explanation of all the facts, although there are a few outstanding difficulties which are not entirely met by either theory. The fundamental postulate of Beilby's theory, and of its subsequent developments at the hands of other workers, is that metals can exist, at the ordinary temperature, in an amorphous or vitreous condition, and that in this condition they are very much harder and stronger than in the crystalline state. Until it shall become possible to produce and to isolate amorphous metal in masses large enough to be dealt with experimentally, it must remain extremely difficult to establish this postulate on an unassailable basis. All that can be done at the present time is to show, by analogy, that the postulate is not in itself improbable, and that its adoption leads to a simple and adequate explanation of a large number of experimental facts. Actually, it is possible to carry the matter a step further and to show that the theoretical conception in question, with certain deductions and developments, has actually led to predictions which have been definitely verified by experiments. In view of these circumstances, the writer regards the theory of amorphous metal as ranking at least high among working hypotheses which have proved themselves useful and illuminating. At the present moment, indeed, even those who on certain grounds vehemently oppose this theory have no consistent alternative to offer which could afford any satisfactory explanation of the great groups of facts which this theory so readily co-ordinates.

With regard to the existence of amorphous metal, we are well acquainted with a whole group of substances which, while commonly occurring in the crystalline form, can yet be readily obtained in the vitreous or amorphous condition.

Quartz (silica) is a striking example, while most varieties of felspar occur in both forms, depending entirely upon the rate of cooling to which they have been subjected after fusion. Tammann has shown [1] that a very large number of typically crystalline bodies can be obtained in the vitreous or amorphous condition by sufficiently rapid cooling (usually chilling) from the molten condition. As a rule, such vitreous substances can afterwards be caused to undergo crystallisation by more or less prolonged heating to some temperature well below that at which the material becomes obviously liquid. Ordinary glass exhibits these phenomena in a very characteristic manner. The only outstanding question, therefore, is whether metals can be obtained in a similar amorphous or vitreous state; and it would seem that if this were not possible, the metals would constitute an exception from the rule which applies to the majority of crystalline bodies. It must, however, be admitted that all ordinary processes of chilling or rapid cooling quite fail to retain molten metal in a non-crystalline condition. This fact may, however, be readily explained by the high velocity of crystal growth in metals and the relatively very great mobility which exists even in solid metals at temperatures near their melting-points. Even in solid iron at 900° C., *i.e.* 600° C. below its melting-point, no known method of quenching is capable of preventing the complete rearrangement of crystalline structure which accompanies the transformation of γ-iron on cooling. This, however, merely serves to explain why it is not easy to produce amorphous metal in bulk by rapid cooling; it does not in any way militate against the possibility that in special circumstances metal may be retained in or converted into the amorphous condition.

§ (2) Crystalline and Amorphous Metal.—These special circumstances would appear to be possibly of two kinds, resulting in both cases from the interplay of atomic forces. In the case with which we are here concerned, Beilby's hypothesis requires that crystalline metal may become converted into amorphous

[1] Tammann, *Krystallisieren und Schmelzen*, Leipzig.

metal at the ordinary temperature as a result of intense local disturbance of crystalline arrangement occurring on the surfaces of slip within crystals undergoing deformation. Beilby's own experimental work on polished surfaces has shown very clearly that under the mechanical pressure of the polishing process a surface film of metal can and does flow, filling up and even bridging over surface inequalities. His evidence further goes to show that such a surface film behaves for a short time like a mobile liquid spreading under the action of surface-tension forces, and that it appears to possess some of the characteristic properties which might be expected of a thin amorphous layer. If such a local conversion from crystalline to amorphous metal can and does occur in a surface layer under the action of a polishing tool, it is not surprising that a similar change should occur on the internal surfaces of slip. On such a surface, layers of atoms are pushed past one another in defiance of the attractive and orienting forces which tend to hold them in their relative positions. Individual atoms must, in such a process, pass from their connection with one set of adjacent atoms into a position where their bonds are attached to a different set of individual atoms, and while passing from one such position of equilibrium to another they must of necessity pass through positions at least approximating to instability. Since finite slip on a single gliding plane necessarily entails displacements of thousands or even millions of inter-atomic spacings, there must be occasion for a great deal of such disturbance. Heat, also, is generated during this process, and at the moment of slip this heat is produced on the gliding planes and, before it has time to become diffused, must set up violent thermal agitation among the atoms near the gliding plane. The mechanical disturbance combined with this thermal agitation may well be conceived as capable of breaking up, locally, and to a more or less complete extent, the crystalline orientation of the atoms. For a brief moment, such a layer of disturbed atoms must be in a condition closely resembling that of a thin film of molten metal. The locally generated heat, however, must be very rapidly dissipated by conduction, and the whole state of agitation must subside very rapidly, so rapidly indeed that the atoms have no time to rearrange themselves in crystalline orientation. It is, in fact, a case of extremely intense chilling from the "molten" state retaining the amorphous or vitreous condition by a particularly violent "under-cooling."

The very approximate picture of local atomic disturbance, resulting in a condition which is, to all intents and purposes, local melting, may be viewed from an entirely different standpoint This has been done by Johnson and Adams,[1] who, on purely thermodynamic grounds, come to the conclusion that what they term "partial" pressure in a solid—that is to say, pressure which acts on the solid phase alone, but from which any liquid phase which may be formed immediately escapes—is capable of lowering the melting-point of most metals quite down to or below the ordinary temperature. These authors conclude that under plastic strain all ordinary metals must undergo local temporary fusion. Nor is the conception of a stress acting on the solid phase alone at all difficult to realise. On a gliding surface the acting stress must of necessity be largely of the nature of a shear, and liquid, once formed, would immediately flow and cease to resist a shearing stress, which would thus be relieved so far as the liquid phase was concerned.

These considerations have been put forward in some detail owing to the fact that certain physicists suggest that vitreous or amorphous metal, being the unstable phase at any temperature below the melting-point, cannot possibly be formed from the stable, crystalline phase at such a temperature. The arguments of Johnson and Adams, however, completely meet this objection, and in any case it is not easy to be certain that, under the conditions of temperature and stress which exist on a gliding plane at the moment of slip, the crystalline phase really is the stable form.

The theory that there is a phase change (crystalline to amorphous) which occurs under plastic strain has recently received interesting confirmation, although only of a preliminary sort, from some experiments carried out by Dr. Sinnatt,[2] who has measured the quantity of heat generated during the plastic extension of a piece of mild steel in the testing machine, comparing it with the heat equivalent of the work done by the tensile forces employed. He has found the somewhat startling result that not much more than 10 per cent of the work done is converted into sensible heat, the remainder being absorbed in some latent form. The generation of amorphous metal, and the consequent absorption of the equivalent latent heat of fusion, offers a simple explanation of this observation.

If it be granted that amorphous metal can exist, and that it can be generated on the gliding planes under the action of plastic strain, we have next to consider what justification there is for the conception that this amorphous metal is very strong, hard, and brittle, or at least incapable of plastic de-

[1] Johnson and Adams, "On the Effect of High Pressures on the Physical and Chemical Behaviour of Solids," *American J. of Science*, March 1913, 35.
[2] Sinnatt, unpublished thesis.

formation. We have, in the first place, the analogy of other amorphous or vitreous substances to guide us. Glass is typical of such amorphous substances, and it certainly suggests a hard and brittle body. But it is necessary at this stage, if the full meaning of the theory of amorphous metal is to be appreciated, to point out that a truly amorphous substance is in reality a liquid—a very much undercooled liquid, but still a substance which possesses the characteristics of a liquid to an extent limited by the degree of viscosity which the conditions of temperature may impose upon it. Thus glass at the ordinary temperature only flows with extreme slowness, although a relatively slight rise of temperature decreases its viscosity enormously (according to an exponential law) so that its truly liquid character soon becomes evident. The properties which we must associate with amorphous metal, therefore, must be considered in careful regard to the temperature scale—an approximately fixed point on the temperature scales of all substances being the true melting-point of the liquid—*i.e.* the temperature at which it is in equilibrium with crystals of its own kind. Amorphous platinum or tungsten, therefore, might well be expected to behave in a very different manner from amorphous lead or zinc. Where the amorphous material exists at a point in the temperature scale far removed from the true melting-point, we should anticipate a very high degree of viscosity coupled with great strength and hardness and little or no capacity for viscous flow. An amorphous material near its true melting-point, on the other hand, while it would still display the characteristic brittleness of a liquid to any rapidly applied stresses, might be expected to give signs of a considerable capacity for slow viscous flow.

In considering the properties of an amorphous substance, however, we need not rely entirely upon analogy with such substances as glass, pitch, etc. Our very conception of the amorphous state as contrasted with the crystalline condition gives rise to one fundamental difference in properties. This results from the very absence, in the amorphous material, of the gliding or slip planes which furnish the crystal with a mechanism for undergoing plastic deformation under the action of stresses far lower than those required to bring about rupture. It has recently been pointed out [1] that all ordinary materials, and metals in particular, are very much weaker than would be anticipated from the calculations of molecular physics. So far has this view been carried that Griffith suggests that the weakness of metals can only be accounted for by the existence within the crystals of a large number of minute ultramicroscopic flaws or fissures—rather of the nature of internal discontinuities. The apparent weakness of ordinary crystalline materials, however, can be explained in a much simpler manner, even if the very high figures for real tensile strength arrived at from the data of molecular physics are accepted. Those calculations refer to the "strength" of the material as if it were the power to resist a direct pull tending to draw the atoms (or molecules) directly apart. Actually, however, they are not pulled directly apart in this manner when metal undergoes deformation or even fracture after plastic strain. What occurs, as we have seen, is a sliding of layers of atoms over one another, and the stress required to bring about such sliding need only be a fraction of that required to bring about direct pulling apart. We can realise the difference from the familiar case of two plates of glass held together by a thin film of water. Direct separation of the plates requires a force which is quite disproportionately larger than that needed to slide the plates over one another until they separate. It is this power of deformation by sliding which, while it renders metals ductile, also renders them relatively soft and weak. They fail, in fact, not by the pulling apart of the atoms from one another, but by sliding of layers of atoms over one another.

If this view is correct—and the actual occurrence of slip in metallic crystals at all events furnishes it with a sound basis of experimental fact—then the absence of ductility and a very much higher degree of strength and hardness are precisely what we must expect to find in amorphous material, where there is no regular orientation allowing of deformation and fracture by slip. It is true that in the majority of substances which we are accustomed to regard as amorphous or vitreous, such as ordinary glass, we do not ordinarily find that high degree of strength which the considerations of molecular physics would lead us to anticipate, but this may possibly be due to the fact that the amorphous character of the material is not, as a rule, completely developed. When melted at a high temperature and quickly cooled, while protected from the access of possible nuclei for crystallisation coming from the air or other surroundings, such substances as glass or vitreous silica may perhaps be obtained in a completely amorphous condition. The presence of minute crystallites in glass in the ordinary condition is rendered probable by its behaviour in regard to fluorescence, and by several other phenomena—particularly the occurrence of a very slight critical point

[1] Griffith, A., "The Phenomena of Rupture and Flow in Solids," *Roy. Soc. Phil. Trans.*, 1920, ccxxi. A, 163-198.

(thermal) in the neighbourhood of 400° C.[1] It would thus seem that in ordinary materials we may meet with the whole range, from the pure amorphous "solid," in reality a perfectly under-cooled liquid, to the crystalline aggregate in which there is only a very thin film of amorphous material between adjacent crystals, with substances of an intermediate character which may be regarded either as consisting of an amorphous matrix in which numerous crystals are suspended, or as a crystalline aggregate in which the amorphous inter-crystalline "film" is relatively very thick.

Leaving the question of amorphous inter-crystalline layers to be more fully discussed below, enough has been said to justify the view that amorphous metals may be expected to be very much harder and stronger than the same metal in the crystalline condition. Ductility, in fact, being dependent upon slip within the crystals, is essentially a property of crystalline matter. A viscous, under-cooled liquid may, of course, undergo deformation of a "plastic" (*i.e.* non-elastic) nature, but the rate at which such deformation can take place is determined by the viscosity, which in turn depends upon temperature—possibly on the temperature difference between any condition under consideration and the normal melting-point of the metal. Yet even where the viscous under-cooled liquid or amorphous metal is sufficiently mobile to undergo appreciable displacement under the action of applied stresses, such deformation is of a different nature from that which occurs within crystals: in the amorphous substance flow must occur by the movement of particles along stream-lines, whereas in a crystal "flow" occurs by a complicated system of slip in which individual atoms do not move in any relation to stream-lines. The most striking difference, however, arises from the influence of the time factor on the deformation of even relatively very mobile amorphous metal.

In the harder metals which are ordinarily submitted to mechanical tests, the amorphous phase at ordinary temperatures—being many hundreds of degrees below its melting-point, is extremely hard and so viscous that it behaves, under all ordinary rates of application of stress, as a quasi-elastic solid, although —as we shall see shortly—very exact measurements show that there must be a certain amount of very slight and gradual flow even in these metals. When, however, experiments are carried out on metals which, while sufficiently near their melting-points, are yet strong enough to allow of the application of large stresses, interesting confirmation of the flow of metal in the amorphous condition can be obtained. This has recently been done in the case of an alloy of zinc with copper and aluminium, containing 4 per cent of copper and 7 per cent of aluminium.[2] In the cast state this alloy is hard and brittle, with a tensile strength of about 23 tons per square inch. When heated to about 250° C., however, it becomes soft enough to undergo rolling, which can be continued as the metal cools. Ultimately, as the result of what is essentially cold-rolling, this alloy may be obtained in the form of sheet metal having a thickness of about 0·02 inch. If such sheet metal be tested in tension in the ordinary way, it gives results which depend enormously on the rate of loading. Thus, with a time of loading of only 3·6 seconds, the tensile strength is found to be 62 tons per square inch, with an elongation of only 9 per cent on 2 inches. If the time of loading is extended to 1 minute 12 seconds, the tensile strength falls off to 27 tons per square inch, while the elongation increases to 42 per cent. A further reduction of the rate of loading until the time occupied is 45 minutes brings the tensile strength down to 16·3 tons, with the remarkable extension of 52 per cent. The manner in which this material flows under the prolonged application of a small load, and its rate of recovery after removal of the load, was also observed, and was compared with the behaviour of glass and pitch in this respect; a most striking resemblance was found. It is not of course suggested that this alloy consists entirely or even mainly of amorphous metal; according to the theory of Beilby and its developments, such material would consist of crystal fragments or remnants embedded in layers of amorphous metal. It was found, for example, that a mixture consisting of 75 per cent of sand and 25 per cent of pitch behaved, under such tests as those here considered, as a typically amorphous material, so that the phenomena described do not demand the presence of any very high proportion of metal in the amorphous condition.

The behaviour of the alloy just described when it is exposed to raised temperatures is of particular interest. It is of course well known that when cold-worked or strain-hardened metal is heated, softening or "annealing" occurs as soon as the temperature is high enough or has been maintained for a sufficiently long time. On the theory of an amorphous phase produced by strain, annealing consists in the resumption of crystalline form by the great bulk of the amorphous material present. At first this recrystallisation may occur without any general rearrangement of the structure, but such general re-

[1] Tool and Valasek, "Characteristics of Glass," *Phys. Review*, Feb. 1919.

[2] Rosenhain, Haughton, and Bingham, "Zinc Alloys with Aluminium and Copper," *Inst. of Metals J.*, 1920, No. 1, xxiii. 261.

arrangement always follows upon more prolonged heating. The result so far as the mechanical properties of the metal are concerned is in all ordinary cases that the strain-hardness disappears and the metal reverts to a more ductile (crystalline) condition. In the case of the peculiar zinc alloy referred to above, however, the phenomena are entirely different. There the "ductility" of the cold-worked metal is due not to crystalline slip but to "stream-line" flow of amorphous metal which in this case is not in an excessively viscous condition. In the crystalline state—as cast, for instance—this metal is hard and non-ductile. We might, therefore, anticipate that any heating which causes the crystallisation of the amorphous phase will immediately destroy the quasi-ductility due to the flow of this phase, and will restore the hardness and brittleness of the crystals. This is precisely what occurs. A few minutes' heating even at 100° C. converts the rolled material into a hard and brittle substance. No other explanation of these apparently anomalous facts has yet been put forward, and they appear to afford very striking evidence in favour of the theory of amorphous metal.

§ (3) Experimental Basis of the Theory. —If the theory that plastic deformation in metals is accompanied by the transformation of a small portion of the metal into the amorphous form be accepted as a working hypothesis, it is found to furnish a key to the great majority of the complex phenomena which are associated with plastic strain, and even to some of the facts relating to elastic deformations. We shall, therefore, consider the more important and well-established facts in relation to the explanations which the "amorphous" theory can furnish.

(i.) *Microscopic Observations.* — We may begin by considering in rather greater detail the microscopic observations relating to strain-hardened material. The formation and microscopic character of "slip-bands" have already been described. If these bands consisted of nothing more than the geometrical displacement of layers of atoms within the crystal, we should anticipate that if a surface on which slip-bands had been developed were afterwards repolished and then again etched, no traces of the bands would be seen. If the deformation has been slight, this is strictly the case, but if severe deformation has taken place, then the etching of such a repolished surface may, and frequently does, reveal traces of lines which bear so strong a resemblance to actual slip-bands that they have sometimes been given that name. Such etched "strain-bands," however, are of a totally different character from the slip-bands proper, and the fact that they occur at all at once suggests that the occurrence of slip must leave behind in the metal some definite change of structure which can subsequently be revealed by etching. It is difficult to believe that such a more or less permanent change of structure can be other than a disturbance of the regular crystalline arrangement, and, therefore, the formation of a layer of more or less amorphous metal. It is typical of these bands that they only appear to any marked extent after severe cold work has been applied to a piece of metal; they are most readily seen in cold-drawn copper alloys, and their direct connection with actual pre-existing slip-bands can be definitely traced in suitable experiments. That these bands are not of the same nature as the "twinned" bands mentioned below is, however, proved by the manner in which freshly-formed slip-bands superposed on the etched strain-bands pass through the latter without suffering the double deflection which is typical of passage through a twinned band.

(ii.) *Cold Work and Hardening.*—Reference has already been made to the fact that cold work results in hardening the metal to which it is applied; thus tensile strain raises both the elastic limit (limit of proportionality) and the ultimate stress (tensile strength) of a metal, and the hardness and strength of the amorphous metal produced on all surfaces of slip has been invoked to explain this hardening. The phenomena, however, are considerably more complex. For while it has been shown that such a test of "hardness" as the Brinell ball test reveals no differences when applied to sections of a rod which has been strain-hardened by tensile overstrain, yet it is well established that in certain metals the rise in the elastic limit in tension is compensated by a fall in the elastic limit in compression.[1] At first sight this fact is not easily reconciled with the supposition that the additional hardness in tension is due to the presence of a hard amorphous material on the previous gliding planes of the crystals. But it must be borne in mind that the phenomena which occur within a crystalline aggregate are not entirely simple, and that the establishment of any type of plastic deformation must necessarily be accompanied by the setting up of more or less severe internal stresses. In perfectly general terms, it may be said that if the structure of a metal is so far in-homogeneous that every element is not equally strained by the external forces which have been applied, then any inequalities of strain must make themselves felt as internal stresses so soon as the external forces are removed. If we assume, for example, that the material is built up of alternate longitudinal strips differing in elastic modulus and in elastic

[1] Bauschinger, *Mitt. a. d. Mech.-Techn. Laborat. München*, 1886, No. 15

range, then a suitable tension applied from outside, and sufficiently large to produce permanent or plastic extension in one set of strips, will strain the others only just to their elastic limit. When the external tension is removed, the whole of the bar will tend to contract by the amount of the elastic part of the extension which had been imposed upon it. But while those parts which had been stressed only up to the elastic limit have the tendency to revert to their original length, the remainder—which had been plastically deformed—will tend to contract only to a much smaller extent. Since all parts of the bar can only contract to the same extent, the bar will remain in equilibrium at a length greater than its original length, with one set of its constituent parts held in compression and the remainder in tension. Such a condition of internal stress will necessarily produce marked effects on the physical properties of the bar as a whole. There must, for instance, be a marked effect upon the position of the elastic limit (of proportionality). If, as is to be anticipated, that constituent which originally possessed the lowest elastic limit is left, after tensile overstrain, in a condition of initial (internal) compression, then the application of an external load will first have to relieve this compression. Thereby the elastic limit in tension of the weaker constituent will be apparently raised, so long as the intensified stress on the stronger constituent does not exceed the elastic limit of that substance. Compression, on the other hand, when applied by external load, will find the weaker constituent already seriously stressed in compression, and an apparent lowering of the elastic limit in compression must result. Provided that one of the constituents is entirely elastic in its behaviour under the whole range of stresses applied, while the other is markedly inelastic, it would follow that the raising of the elastic limit in tension would be exactly counterbalanced by an equal lowering of the compression limit. If, however, there is any plastic yielding or even a slow "creep" in the harder constituent, then this relation would no longer hold good.

The explanation suggested above for the shifting of the elastic limits in some metals as a consequence of plastic strain has intentionally been kept very general, and it might perhaps be applied to any duplex alloy consisting of two widely different micro-constituents. But it would be necessary to assume that both the elastic limits and the elastic moduli of these two phases should be very different—and the latter constants at all events do not vary much throughout the alloys belonging to the same series. Actually, the explanation is best met by regarding the soft crystalline metal as the "weaker" constituent, and looking upon the amorphous metal formed on slip-planes and also existing in the crystal boundaries (see below) as the very much harder and more elastic material. For, although we are to regard amorphous metal as essentially of the nature of a highly viscous liquid, yet these extremely viscous substances behave as quasi-solids unless an extremely long time is given for flow to take place. In all ordinary tensile testing, and in most elasticity experiments, the time occupied is very brief. Under such conditions, the amorphous phase of the less fusible metals may be regarded as a solid having very high tensile strength and a very high "elastic limit," and for all ordinary purposes it therefore fulfils strikingly the requirements of the "harder constituent" discussed above. If the theory here suggested is correct, however, it would be anticipated that the internal stresses in cold-worked material should, in the course of years, disappear, owing to the gradual flow of the amorphous material. If this were the case, one would anticipate that in the course of many years the elastic limits displaced by straining should gradually tend to resume their normal values. This experiment, however, does not appear to have been tried, and there is no evidence to suggest whether the relief of such internal stress should occupy years or centuries at the ordinary temperature. That such relief may—and probably does—occur at slightly elevated temperatures is, however, clearly indicated by the marked effect of exposure to slightly raised temperatures on such materials as cold-drawn steel tubes in the process known as "blueing."

(iii.) *Dalby's Experiments.*—Beyond the phenomena already indicated, there is a whole series of others connected with plastic strain which require not only explanation at the hands of any satisfactory theory of strain-hardening, but, in the first instance, still await further investigation. We shall refer, below, to the phenomena of elastic after-working, and other minor features of the elastic behaviour of metals. Here we will only refer to the so-called semi-plastic state met with in iron and mild steel. This has been studied by various workers, notably Muir [1] and Dalby.[2] In the case of nearly pure iron, the phenomenon in question is that if a piece which has been overstrained in tension is relieved of its load, and is then again gradually loaded and its behaviour observed by means of an extensometer, it is found to be in a semi-plastic state, *i.e.* starting from nearly zero load, the stress-strain diagram shows a curve instead of the normal straight line corresponding to the elastic stage of strain.

[1] Muir, J., *Roy. Soc. Phil. Trans.* A, 1900, clxiii. 1.
[2] Dalby, W. E., *Roy. Soc. Phil. Trans.* A, 1921, ccxxi. 117; also *Roy. Soc. Proc.* A, 1923, ciii. 8.

If the specimen is alternately loaded and unloaded, the stress-strain diagram takes the form of a loop, typical of the class of phenomena which, from their analogy to what takes place in a magnetic cycle, are generally called "hysteresis." From the point of view of any theoretical explanation, however, the most interesting feature of this phenomenon is that after a fairly lengthy period of rest or immediately on exposure to a very slightly elevated temperature, such as 100° C., the material, at any rate in the case of iron and mild steel, recovers its elasticity—the hysteresis loop vanishes and a test yields a straight elastic line up to the new raised limit of proportionality. Dalby has recently shown, by means of an optical indicator specially designed for rapidly tracing these stress-strain loops, that the behaviour of different metals varies widely in regard to this phenomenon. In a few metals it does not occur at all; in a few there is rapid recovery as described above, while in others even prolonged exposure to 100° C. does not bring about recovery.

While the whole of these phenomena have not yet been studied sufficiently to allow a satisfactory explanation to be formulated, it appears probable that the variation in behaviour found by Dalby depends upon the wide differences in the viscosity of the amorphous phase which must exist as between such metals as steel and an aluminium alloy. Beilby[1] has suggested, without particular reference to the facts now under discussion, that the amorphous phase when first formed is in a special "mobile" condition, and his evidence as to the flow of surface films of amorphous metal furnishes considerable support for that view. This idea also appears to offer an attractive possibility of explaining the temporary "mobility" (*i.e.* semi-plasticity) of overstrained metals. On the other hand, this view meets with the obvious difficulty that, if mobile amorphous layers exist even for a few minutes—not to say hours or days—on the gliding planes of crystals, why should not such amorphous material avail itself of this very mobility to undergo recrystallisation? The writer therefore inclines to the view that the "temporary mobile phase" is probably confined to surface films, whose character is influenced by conditions—particularly of pressure—entirely different from those existing within the mass of metal, and that the stress-strain hysteresis phenomena discussed above are to be ascribed to the interplay of internal stresses and the gradual accommodation—in some metals—of the amorphous material to those stresses. Rise of temperature would undoubtedly facilitate such accommodation, but it is difficult to see why or how it should accelerate the transition of a "mobile" into a rigid amorphous condition.

(iv.) *Brittleness and Fracture.*—The phenomena of plastic deformation which have so far been considered are mainly those connected with relatively moderate degrees of deformation occurring at the ordinary temperature. We have next to consider what occurs when deformation is pushed to the point of fracture or when fracture occurs without much deformation under various circumstances. Taking the case of "brittle" fracture occurring under a single loading, we have a relatively simple case. If the metal is one in which crystalline structure is well developed, fracture occurs by direct cleavage or separation along certain planes of the crystals. Even in such a brittle metal as bismuth or antimony, fracture occurs by this process of cleavage across the crystals and not by the separation of the crystals from one another, whether the cause of fracture be a steady pull or a blow. On the other hand, there are materials—but never simple metals—in which fracture apparently occurs along the boundaries of the crystals. If, for instance, gold is rendered brittle by the addition of a small percentage of bismuth, it appears to fracture in this manner. Actually, the presence of the bismuth gives rise to a distinct micro-constituent which forms a brittle and weak envelope around the crystals of the gold. Fracture occurs through these brittle envelopes, and thus appears to follow the crystal boundaries of the gold although in reality it occurs in what are probably crystals of the brittle constituent. The individual gold crystals can be separated from such an alloy and are then found to be perfectly ductile.[2] Similar cases of apparent inter-crystalline brittleness are found in a number of metals, including unannealed steel castings in which sulphide of iron plays the part of a brittle inter-crystalline medium. In all such cases, however, the type of fracture owes even its apparent inter-crystalline character to the presence of some special impurity or defect.

In metals whose crystalline character is not so strongly marked by the development of definite cleavages, fracture may take a somewhat different form. For instance, in some materials, such as hardened steel, the crystalline structure is extremely minute, and the mass of the material may easily exhibit a typically conchoidal fracture such as is typical

[1] Beilby, *British Association Report, Glasgow*, 1901; "Surface Flow in Crystalline Solids," *Roy. Soc. Proc.*, May 1903, lxxii.; "The Surface Structure of Solids," *Journ. Soc. Chem. Ind.*, Nov. 1903; "The Hard and Soft States in Metals," *Phil. Mag.*, Aug. 1904; "The Influence of Phase Changes on the Tenacity of Ductile Metals," *Roy. Soc. Proc.* A, 1905, lxxvi. 462; "The Hard and Soft States in Ductile Metals," *Roy. Soc. Proc.* A, 1907, lxxix.; "Surface Flow in Calcite," *Roy. Soc. Proc.* A, 1909, lxxxii.; "The Hard and Soft State in Metals," *Inst. of Metals J.*, 1911, No. 2, vi.

[2] Arnold, "Discussion on Fourth Report, Alloys Res. Com.," *Inst. Mech. Engs. Journal*, Feb. 1897.

of glass. Such fractures occur principally in materials which are either wholly amorphous or consist of minute crystallites embedded in an amorphous matrix.

In metals which are more or less ductile, the type of fracture depends very much upon the manner in which it is produced. The nature of the fracture depends entirely upon how much—if any—plastic deformation occurs before rupture. A highly ductile piece of wrought iron, for example, can be made to break with a crystalline cleavage fracture, if it is first given a sharp notch or incision and is then struck a sharp blow. In the absence of a notch, such material would bend double in the cold without showing a crack, or would undergo a large amount of extension before fracture under a tensile test. However it may be broken, the metal remains equally crystalline in its internal structure, so that it is wrong to speak of such material being "fibrous" in one case and "crystalline" in the other: these terms can at most be applied to the type of fracture.

When a ductile metal is broken after severe plastic deformation, as in a tensile test, the constituent crystals have first undergone the process of deformation by internal slip to an extreme degree. At the same time, layers of hard amorphous metal have been formed on successive gliding surfaces until, finally, the crystals are so fully interlaced with amorphous layers that further plastic yielding becomes impossible and fracture occurs. This fracture still takes place across the crystals, but not on smooth, regular cleavage planes; such planes have become disturbed and stepped, and criss-crossed with layers of amorphous metal, so that the final fracture takes a somewhat zig-zag path across the much-elongated remnants of the original crystals. The result is a fracture having a fibrous, silky appearance, but under the microscope its essentially trans-crystalline character is still quite evident.

(v.) *Duplex Alloys.*—The whole of the phenomena of strain and fracture become much more complex when one deals not with a simple metal but with a duplex alloy. In such materials, one of the two constituents is always very much harder, stronger, and less ductile than the other. The function of such a harder constituent is to stiffen up the alloy as a whole so as better to resist the tendency towards plastic deformation when stress is applied to it. The crystals of a harder constituent dispersed among the softer ones serve to support the latter at their edges and to increase the stress required to produce slipping. When deformation does occur, however, the harder and relatively brittle constituent as a rule also undergoes deformation. Apparently the surrounding softer material serves to hold it together while undergoing slip, whereas, if left to itself, such slips would develop into cleavage fractures. Thus in a mild steel which has been strained in tension, the relatively hard pearlite is elongated nearly as much as the soft ferrite. When, however, plastic strain has gone to a certain length, the harder constituent appears to undergo a species of internal fracture which rapidly leads to the fracture of the whole piece. This resulting fracture—when produced after serious plastic deformation—appears to run indifferently through the two constituents.[1] On the other hand, if such a metal is broken either by shock or fatigue (see below), then the fracture as a rule appears to avoid the harder constituent and to follow, as far as possible, the cleavage or gliding planes of the ferrite. Whichever type of fracture may occur, however, it is clear from what has been said as to the relative parts played by the two constituents of a duplex alloy that the powers of resistance of the material must be greater the more intimately the two constituents are associated, *i.e.* the finer the "grain" of the micro-structure. This inference is fully supported by observation.

(vi.) *Fatigue.*—The phenomena known as "fatigue" in metals have now to be briefly considered from the point of view of the internal structure and mechanism of metals. An account of the phenomena themselves is given in the articles[2] treating of the elastic properties of material, so that they need only be briefly mentioned here. The fundamental fact which must be explained by any satisfactory theory of the internal structure and behaviour of metals is that a stress which when steadily applied is quite insufficient to break a given material will yet bring about fracture if applied and reversed a large number of times. For each material there appears to be a limit of stress—sometimes termed the safe range of alternating stress—any stress below which can be applied and reversed indefinitely without causing failure. Any stress above this limit, on the other hand, produces fracture, generally in less than one million reversals, or, if the stress is far above the safe limit, fracture may occur in a few thousand reversals.

Microscopic observation has provided a clue to the nature of these occurrences, since it has been found[3] in the first instance by Ewing and Humfrey, and subsequently confirmed by others,[4] that such fatigue failure commences by the occurrence of a very slight amount of plastic deformation in one or in a

[1] Rosenhain, "Deformation and Fracture in Iron and Mild Steel," *Iron and Steel Inst. Journ.*, 1906.

[2] See article "Elastic Constants, The Determination of," Vol. I.

[3] Ewing and Humfrey, *Roy. Soc. Phil. Trans.* A, 1902, cc.

[4] Stanton and Bairstow, *Proc. Inst. Civil Eng.*, 1905–6, clxvi. Pt. 4.

few isolated crystals which happen to be so placed in regard to their crystalline orientation relatively to the directions of the applied stresses that slip is specially facilitated. Such plastic deformation is, of course, extremely minute when considered as a percentage change in the dimensions of a test-piece, but it is appreciable as a deformation of an individual crystal. Now the slip which occurs in such an individual crystal on the first application of a stress becomes reversed when the stress itself is reversed, and thus at each alternation the gliding surfaces are rubbed over one another, backwards and forwards at each reversal. For a considerable number of reversals, nothing further occurs—if at this stage the metal is allowed to rest, or if it is heated to an annealing temperature, no damage has been done and nothing further occurs. But, after a certain stage has been reached—and the time required to reach it will depend upon the amount of slip which occurs, and therefore on the intensity of the applied stress—a further change makes itself felt. Up to this stage, a polished and etched cross-section of such material shows no trace of the places where slip has occurred, but in the second stage this is no longer the case—fine lines appear on such sections, and as the process continues these become wider and more numerous until they develop into obvious fissures or cracks. Once such a crack has been formed in a single crystal, that individual ceases to bear any part of the stress, and additional stress, in a localised form, is thrown upon the adjacent crystals. These undergo slip and fissuring in their turn, and in this way the fissure makes its way across the whole thickness of metal and fracture results.

If this view of the phenomena of fatigue is correct—and the microscopic evidence is very convincing so far as the facts are concerned—it would follow that the only " safe " range of alternating stresses is one which does not produce even the most localised amount of slip anywhere in the material. In one sense this is the " true " elastic limit, but since the plastic deformations in question are so very minute, the most sensitive extensometer as a rule fails to detect any plastic deformation at stresses considerably higher than the fatigue range. In this sense, one may regard the determination of the safe range under fatigue as essentially a determination of the real elastic range of a material. There are, however, reasons for thinking that even this is a somewhat arbitrary distinction in an aggregate which consists of truly crystalline and elastic material together with a varying amount of an amorphous, quasi-elastic, but essentially viscous material.

The manner in which, under fatigue stresses, a surface of repeated slip becomes converted into an actual fissure requires some consideration. If Beilby's view, that the amorphous material when first formed is temporarily mobile, be accepted, there is little difficulty in supposing that this temporarily mobile material may be simply squeezed out from between the slipping surfaces. Even then, however, the question remains, where does it go ? The solid metal can scarcely be regarded as providing interstices large enough to allow room for such material, and at first sight this appears to be a serious difficulty. A moment's consideration, however, reveals the fact that fatigue fractures always commence at the surface of a piece of metal. Often they are localised, if not actually initiated, by some surface irregularity, but in any case the most severe stresses generally occur at or close to the surface. Further, it is quite evident that, given even uniform distribution of stress, a crystal lying in the actual surface layer of the metal is more favourably situated for undergoing local slip than any crystal within the mass of the material. With this consideration, however, the difficulty of the disposal of the products of attrition by crystal slip disappears. Further, it lessens the difficulty of accepting the temporary mobility of amorphous material, since we have already seen that Beilby's evidence concerning surface flow of solids [1] has made it evident that at or near the surface such rapid flow of freshly formed amorphous metal may take place.

The discussion of the phenomena of fatigue, and their explanation by the theory just described, cannot be carried further within the limits of the present article, but it is desirable to refer to a very ingenious theory recently put forward by Griffith.[2] This author accepts the view outlined above as to the part played by the phenomena of slip in plastic deformation, and also accepts the view that fatigue failure commences by local deformation of individual crystals. He, however, does not accept the view that slip surfaces become converted into fissures by attrition. He endeavours, on the contrary, to explain the phenomena by the hypothesis that metals, in their ordinary condition, contain a large number of very fine cracks or fissures—only a few " molecules " in thickness, and really of the nature of minute gaps in the crystal structure. By the existence of these " cracks " he seeks to explain the weakness of metals as compared with the strength calculated from the data of molecular physics, and he suggests that in plastic deformation these cracks are increased in size, thus accounting for the relatively small change in density which is

[1] Beilby, *loc. cit.*
[2] Griffith, A., " The Phenomena of Rupture and Flow in Solids," *Roy. Soc. Phil. Trans.* A, 1920, ccxxi. 163-198.

accompanied by a change in the elastic modulus which he regards as disproportionate. Under fatigue stresses, such internal flaws simply spread, bringing about fracture when they have become sufficiently extensive. The difficulties of such a theory are, however, obvious. The fact that cold-worked metal is both harder and stronger than it was before the application of plastic strain scarcely suggests that it is a material in which internal cracks have been extensively opened up. There is also the fact that the electrical resistance of strain-hardened metal is only very slightly different from that of the soft material—a fact which, on Griffith's theory, can only be explained on the further assumption that the internal "flaws," while wide enough to act as fissures so far as mechanical strength is concerned, are narrow enough not to affect electrical conductivity, regarded as electronic in character. Taken as a whole, this theory, while very ingenious, appears to the writer to be highly artificial, and until some evidence can be produced to establish the real existence of internal fissures of the kind postulated by Griffith, it would seem wise to regard the whole hypothesis with caution.

§ (4) The Fracture Path.—In our discussion of the behaviour of pure (or "simple") metals under strain we have hitherto confined our attention almost exclusively to the behaviour of the constituent crystals considered more or less as independent units. Actually, however, the behaviour of any ordinary piece of metal depends upon a number of additional factors which are related to the manner in which the crystals of the aggregate are connected together. At first sight one would perhaps expect to find that the crystals themselves are very much stronger than the aggregate of which they form a part, so that when such an aggregate came to be broken, whether by a sudden blow or by any process of gradual disintegration, the individual crystals would become separated from one another—*i.e.* that the path of fracture would ordinarily follow the inter-crystalline boundaries. This, however, is conspicuously *not* the case. There are certain special cases, occurring under conditions which are now well recognised, where inter-crystalline fracture occurs, but in the vast majority of cases pure simple metals, and even the great majority of strong and ductile alloys, break by fractures which pass through the crystals and not around them. So much is this the case that the inter-crystalline boundaries have come to be recognised as sources of strength rather than of weakness. Superior mechanical properties are, in almost all metals, associated with a fine-grained structure, *i.e.* one in which the constituent crystals are small, and there seems to be every reason to believe that the advantage of a minute micro-structure resides in the strengthening effect of the crystal boundaries, which are more numerous and more closely spaced in such a structure than in a coarsely crystalline one.

We are thus confronted with the remarkable fact that the cohesion between adjacent grains or crystals is greater than that within the crystals themselves. This inference is further strongly supported by microscopic examination of the character of slip-bands in the neighbourhood of crystal boundaries. In these regions the bands are distorted in such a manner as strongly to suggest that the free occurrence of slip on the crystalline gliding planes is to a considerable extent inhibited by forces derived from the region of the crystal boundary itself. Any theory which purports to explain how inter-crystalline adhesion is brought about must, therefore, explain this fundamental fact that in normal metals this adhesion is greater than the cohesion existing across cleavage or gliding planes within the crystal.

The simplest view of the nature of crystal boundaries, which is adopted, among others, by Tammann,[1] assumes that the strictly crystalline orientation of each crystal is preserved until its outlying atoms are so close to those of the next crystal that there is no room for further atoms on the space-lattice system of either crystal. On this view, certain of the atoms would be common to both crystals, while at intermediate points, where the two space-lattices do not fit properly, there would be interstices—in fact, the existence of such inter-crystalline interstices is an essential part of this theory. This view, however, fails entirely to explain the marked strength of the inter-crystalline boundaries, since a region where numerous interstices exist must necessarily be weaker and not stronger than the mass of the solid crystal. Further, if such interstices exist in the boundaries, these must form insuperable obstacles to crystal growth and analogous phenomena which occur so readily in metals at temperatures very far below their melting-points. Beyond this there are a whole series of further objections to this theory which are best dealt with in other connections. Even the strongest supporters of this theory appear to adopt it mainly on account of what they regard as a fundamental objection to the only alternative hypothesis yet put forward. This objection arises from the view that, because it has not yet proved possible to produce amorphous metal in large masses by some such process as the under-cooling of liquid metal, therefore metal cannot exist in the amorphous condition even in minute amounts, or—to put

[1] Tammann, *Zeitschr. f. Elektrochem.*, 1912, xviii. No. 16.

it in another way—that, since metals are known to possess considerable tendency to form crystals and to possess considerable velocities of crystallisation, therefore, once the crystallisation of a liquid metal has commenced, during freezing, that process must go on until the *whole* of the metal has become crystalline. To the writer and to many metallurgists, these inferences do not appear to be justified. As already described, metal has recently been prepared in a condition in which its properties correspond in a striking manner with those to be looked for in an aggregate consisting to a considerable extent of amorphous matter, while the evidence now to be described also serves to show that even cast or fully annealed metal exhibits properties which can best be accounted for by the view that layers or films of amorphous metal always exist in the inter-crystalline boundaries. Unless all these facts of observation and experiment can be better explained on some other view, it appears to the writer that they must considerably outweigh the purely *a priori* argument that metals cannot remain in an amorphous condition between closely adjacent crystals.

The view that inter-crystalline cohesion in a crystalline aggregate arises from the presence, between the crystals, of a layer of amorphous metal acting as a species of "cement," was arrived at more or less simultaneously by several workers following different lines of thought and experiment. Thus Sears,[1] investigating the elastic behaviour of metal rods, came to the conclusion that some of the facts could best be explained by supposing that the metal consists of crystalline particles enclosed in an amorphous matrix or envelope; Osmond [2] states that he sees strong reasons for believing that minute amorphous layers exist between adjacent crystals; while Bengough [3] gives the first definite published statement of the "amorphous cement" theory. The present writer had, however, carried out experimental work in an endeavour to establish this theory prior to the publications mentioned, and the first account of such experimental evidence was published by Ewen and the writer in 1912.[4] Since then, partly as the result of controversies arising out of the theory, a large amount of further evidence has been obtained, with the result that any rival theory is now faced with a large range of experimental fact, which has, in many cases, been determined as the result of predictions based upon the theory of an amorphous "cement."

The evidence relating to the behaviour of inter-crystalline boundaries in metals, and particularly in pure metals, may be conveniently divided into two distinct branches, which deal, one with the purely physical or mechanical behaviour of the boundaries, and the other with chemical and physico-chemical phenomena associated with them. The former group may be considered first, particularly since reference has already been made to the relatively great strength of the crystal junctions in pure metals at ordinary temperatures. Very interesting considerations arise, however, if the effect of varying temperatures on the inter-crystalline cement be considered.

§ (5) Strength and Temperature.—The "amorphous cement" theory implies, fundamentally, that the inter-crystalline layer possesses the essential properties of an under-cooled liquid, and it is a universal property of all liquids, whether under-cooled or not, that their viscosity rises rapidly with falling temperature, the rate of rise per degree of temperature drop varying widely, but being generally very rapid indeed over some particular range of temperature. The actual viscosities of liquid metals at their melting-points are only very approximately known, and although metals differ considerably from one another in this respect, their viscosities in the just-molten condition are all of the same order. Similarly, we do not know the exact shape of the temperature-viscosity curves of metals for temperatures below their melting-points, but the analogy of all known liquids enables us to assume with a fair degree of certainty that they also follow a similar curve indicating an increase of viscosity with falling temperature which may, however, differ very widely in amount from one metal to another. Broadly, however, it is quite reasonable to anticipate that an under-cooled metal will be enormously viscous if observed at a temperature 1000° C. below its melting-point as compared with another observed, say, 300° C. below its own melting-point. In a very rough general sense, in fact, we may regard the melting-point as indicating the relative temperature-scale in regard to viscosity for each metal. In such metals as lead and tin, for example, we should thus expect that the amorphous phase should be relatively mobile or non-viscous, with the consequence that the metals could not be severely hardened by cold work (strain), and that recrystallisation after strain should occur even at the ordinary temperature — both anticipations being fully borne out by observation. Zinc, having a higher melting-point, should be capable of being more fully hardened by strain and rather less liable to recrystallise at ordinary temperatures, although probably still doing so in the course of a long time. Finally, iron should be expected to undergo

[1] Sears, *Cambridge Phil. Soc. Trans.* xxi. 105.
[2] Osmond, Discussion on "Transformations of Steel," *Iron and Steel Inst. J.*, 1911, No. 11.
[3] Bengough, *Inst. Metals J.*, 1912, vii. 176.
[4] Rosenhain and Ewen, *Inst. Metals J.*, 1912, viii. 2.

extreme degrees of strain-hardening and should be unable to undergo recrystallisation without considerable heating. In these respects also the indications of the theory are fully in accord with facts. But it is possible to pursue the matter further by considering not the relative viscosity to be anticipated in different metals at the same temperature, but the changes of viscosity which must occur in the same under-cooled metal at different temperatures.

At or near the melting-point one would expect the viscosity to be relatively low. With falling temperature it would be anticipated, as indicated above, that the viscosity will increase, comparatively slowly at first, and then, for a certain range, very rapidly. If, now, we consider the effect of such changes in viscosity on the behaviour of the metal under ordinary stresses, as, for instance, in a tensile test, we see at once that it must depend entirely upon the time during which stress is applied to the metal, assuming that it does consist in part of amorphous material. While the viscosity of the amorphous metal is still comparatively low, the time effect will be considerable and obvious, much as it is in the case of pitch, where an attempt to draw it out or bend it rapidly leads to brittle rupture, while a slight stress applied for a long time brings about a large amount of flow or deformation. At lower temperatures, where enormously higher viscosities have to be dealt with, the time effect will not be so apparent, for the simple reason that under any stress which can be applied without causing immediate rupture, the rate of flow is so very minute that extremely long periods of time—running in the case of the high-melting metals tested at ordinary temperatures probably into years or even centuries—must elapse before appreciable movement takes place. Only under the most delicate forms of test, where sensitive extensometers are employed, therefore, are any signs of viscous behaviour to be found in such materials as iron and steel.

Under any ordinary tensile test, in which the load is applied at a moderately fast rate, therefore, material of a certain (fairly high) viscosity will appear to possess a fairly definite tensile strength. At high temperatures, where the viscosity is relatively low, this apparent strength will be low also, while at low temperatures the amorphous substance will possess an apparently extremely high strength and hardness. In seeking to apply this inference to actual specimens of metal, however, it is essential to bear in mind that, as a rule, these will consist of an aggregate of crystals held together—on our hypothesis—by a "cement" or layer of viscous under-cooled amorphous metal. The behaviour under a tensile test will therefore depend entirely upon whether the crystals or the cement are weaker. So far as is known, there is no reason to suppose that the resistance of crystals to slip and rupture depends to any considerable extent upon temperature. No doubt the greater mobility of the atoms at high temperatures tends to render crystals softer when hot, but that the enormous increase of viscosity in liquids with falling temperature cannot be paralleled by any corresponding change in the strength of solid crystals is evident from the fact that the increase in total strength found in crystalline metals over wide ranges of temperature is not very great; such a change may be as much as ten to one or fifty to one, while changes of viscosity may be several thousandfold. We should therefore anticipate that at high temperatures, not far below the melting-point of a metal, the crystals will be much stronger than the amorphous material of the same composition, even under the conditions of an ordinary test. At low temperatures, on the other hand, we should anticipate the reverse relationship, the crystals being much softer and weaker than the amorphous material unless very long periods of time are involved. This relationship may be expressed diagrammatically by the curves in *Fig.* 6, where the full line represents the assumed relationship between strength and temperature in the crystals of a metal, while the dotted line represents the same relationship for the apparent strength of the same metal in the amorphous condition. Whatever the precise shape of the two curves may be in any actual case, the two curves must cross at some point below the melting-point. Jeffries [1] has called this crossing-point, where the strength of the crystalline phase is the same as the apparent strength of the amorphous phase, the "equicohesive" temperature. This name, however, appears to be somewhat misleading, since the apparent strength of amorphous material must depend on the rate of loading or the time during which stress is allowed to act.

FIG. 6.

At temperatures above this crossing-point of the two curves in *Fig.* 6 we should anticipate that both deformation and rupture should occur mainly or entirely in the amorphous inter-crystalline cement of a crystalline aggregate, while at temperatures below that of the crossing-point, deformation and fracture

[1] Jeffries, Z., *American Inst. of Metals J.*, 1917–18, vol. xi.

should occur mainly or entirely in the crystals. The behaviour of most metals under stress at ordinary temperatures fully bears out the latter inference; it was, in fact, as has been indicated above, the need for an explanation of the relatively great strength of inter-crystalline boundaries which first gave rise to the theory of an amorphous inter-crystalline cement. Fracture at ordinary temperatures and in fairly short times always occurs mainly through the crystals of a metal and not by the pulling apart of the crystals from one another.

At high temperatures, near the melting-point of the metal, however, a very different state of affairs is encountered. One of the first observations of this kind was made by the writer and J. C. W. Humfrey [1] in their observations on the mode of deformation of iron at high temperatures. They found that, at temperatures in the vicinity of 1000° C., while deformation of the crystals (of γ-iron) still takes place by the formation of slip-bands, etc., yet the amount of deformation occurring in the crystals themselves is much smaller than in iron at the ordinary temperature, and that this is compensated by a greatly increased amount of displacement occurring at the crystal boundaries. Corresponding to this behaviour, they also found that the apparent tensile strength of the metal at those temperatures depends upon the rate of straining, and that the law connecting rate of extension with the stress applied is of a parabolic form strongly suggesting that the deformation—which occurs mainly in the boundaries—is due to the flow of a viscous liquid.

The matter was carried further by the present writer and Ewen,[2] who showed that, under very light stresses and at temperatures a few degrees below the melting-point, a number of metals, including lead, tin, aluminium, antimony, silver, and gold, break with a purely inter-crystalline fracture, the crystals being cleanly pulled away from one another without themselves undergoing any appreciable amount of deformation. It was suggested that this observation might be explained by the melting of very thin layers of more fusible impurities lying in the crystal boundaries, but the experiment, when repeated with gold of very high purity (believed to be pure, even as regards gases, certainly to one part in 100,000, and probably to one in 1,000,000), still gave the same result.

The observations described above, which in one case at least were made in order to test predictions based on the theory of an amorphous inter-crystalline cement, must be regarded as furnishing strong support for that theory. A number of other lines of evidence has, however, been obtained in further confirmation. One of these relates to the behaviour of metals in regard to volatilisation when heated *in vacuo*. Metals, including iron, silver, and platinum, undergo an appreciable amount of volatilisation when raised to relatively high temperatures *in vacuo*, and this volatilisation, combined with certain other actions, serves to reveal their structure when a previously polished surface is heated in a vacuum high enough to prevent tarnishing of the surface by oxidation. At the same time the piece of metal undergoes an appreciable loss of weight. On the basis of the amorphous cement theory it was argued that metal in the liquid phase, even if strongly under-cooled, should have a higher vapour pressure at the same temperature as crystalline metal — if only on the ground that the latter is the stable phase. It was therefore anticipated that volatilisation on heating *in vacuo* should occur preferentially from the crystal boundaries, and therefore that a piece of metal consisting of a large number of minute crystals should lose weight more rapidly than a corresponding piece of the same metal consisting of relatively few and large crystals. Experiments made by the writer and Ewen [3] on zinc, silver, and copper confirmed this conclusion to a striking extent.

§ (6) Further Considerations.—A number of other properties which would reasonably be anticipated in an amorphous inter-crystalline layer possessing the general character of under-cooled liquid has also been considered, and further experimental evidence in support of the amorphous cement theory has been obtained. Thus it is to be confidently anticipated that the amorphous and less stable phase would be more chemically active than the stable crystalline material. The crystal boundaries would therefore be likely to act as favourable ground for all kinds of chemical action, particularly since the nature of a liquid would probably allow of diffusion with greater ease than the more rigid structure of a crystal. These anticipations are confirmed by a large variety of observations. Thus pure cast-lead, if exposed for some time to the action of dilute nitric acid, is attacked mainly in the crystal boundaries. If the minute fissures thus produced are opened out by the action of some external stress, this attack proceeds rapidly until the constituent crystals become entirely separated. In brass also corrosion frequently occurs at crystal boundaries, particularly when the material is under stress, and such corrosion facilitates "season cracking" (see below). Still more striking is the action of mercury, or of solutions of its soluble salts. When such a solution is brought into contact with brass

[1] Rosenhain and Humfrey, *Iron and Steel Inst. J.*, 1913, i.

[2] Rosenhain and Ewen, *Inst. Metals J.*, 1913, x. 2.

[3] Rosenhain and Ewen, *Inst. Metals J.*, 1912, viii. 2.

which is under considerable stress almost immediate fracture results, metallic mercury rapidly penetrating along the crystal boundaries. In some kinds of brass (consisting mainly of the β phase) this action of mercury is sufficient to separate the crystals from one another without the aid of stress, although the action is more rapid if the metal has previously been slightly strained. On aluminium also mercury has a similar action, dissolving away the inter-crystalline material at a much faster rate than the bodies of the crystals.

Recently, observations have been published indicating that other substances besides mercury are capable of producing a preferential dissolving action on the inter-crystalline material. Thus Dickenson[1] has described a case where the solder on a piece of "manganese bronze" became liquid owing to the high working temperature of a machine, with the result that the liquid solder rapidly penetrated the crystal boundaries of the metal and caused its disintegration. Rawdon[2] has described a case in which pure copper is rendered extremely brittle by the penetration along its crystal boundaries of metallic sodium liberated electrolytically from a bath of fused sodium salt. There is also some evidence[3] that gases pass into metal mainly along the crystal boundaries. In view of the fact that the existence of anything in the nature of real interstices in the crystal boundaries is precluded by the high mechanical strength of these boundaries at all ordinary temperatures, the inference from the observations just described is that there is an interstitial material in the crystal boundaries which differs in physical and chemical properties from the crystalline metal, and that this has properties which closely correspond to those which might be anticipated from under-cooled amorphous metal.

The view of Sears,[4] that the elastic behaviour of metal rods can best be explained by regarding the metal as a mixture of elastic solid and viscous material, has already been referred to. Recently, however, it has become possible to verify this view in a striking manner, since pieces of metal of a substantial size, and consisting entirely of a single crystal, have become available, and results of very great importance have been reached in the recent Bakerian Lecture[5] by G. I. Taylor and Miss Elam. Study of the manner of formation of large crystals under the most favourable conditions has shown that, by drawing a wire through a furnace kept at a suitable "annealing" temperature at the right rate to keep up with the rate of crystal growth, a single crystal can be caused to "grow" in such a way as to occupy several feet of the wire. This process has been carried out successfully both with tungsten and zinc. "Single-crystal" wire of this nature lends itself to experiments of the sort indicated, and some work of this kind has been carried out by Wartenberg.[6] He finds that the physical behaviour of the "single-crystal" wire differs very markedly from that of ordinary wire consisting of a crystalline aggregate. The various anomalies of behaviour, such as elastic after-working, creep, etc., which have led others to suspect the presence of a viscous material in the wire, disappear entirely in the absence of crystal boundaries, and these experiments therefore furnish important confirmation of the "amorphous cement" theory.

§ (7) Season Cracking.—Another series of phenomena remain to be considered in the present connection. Some of the more common of these have long been known by the unsatisfactory name of "season cracking." These have been most widely observed in brass which, in certain circumstances, appears to undergo spontaneous cracking some considerable time after its manufacture. As a rule such cracking is observed only in articles which have been made by some process in which the metal is severely cold-worked, such as drawing, stamping, or spinning. It was at one time thought that the failure of the metal in such conditions was due to its existence in a highly unstable cold-worked condition, which might perhaps result in some sort of recrystallisation accompanied by a change in volume leading to cracking. It is now fully recognised, however, that the essential condition for "season cracking" is the presence in the finished article of internal stresses of considerable magnitude, and that the resulting fracture is of a special nature, brought about by the long-continued action of these internal stresses. The characteristic feature of the fracture is that it follows the crystal boundaries so that the crystals are pulled away from one another. The same material broken in the testing-machine breaks with a normal fracture running through highly distorted crystals.

Recently, the present writer and Archbutt[7] have studied this type of failure on rather wider lines, including in their observations such different metals as brass, certain aluminium alloys, lead, and even mild steel. They find that in all these metals, and probably in many others, a purely inter-crystalline fracture can be produced by the long-continued action of stresses much smaller than those

[1] Dickenson, *Inst. of Metals J.*, 1920, ii.
[2] Rawdon, *Mining and Metallurgy*, 1920, No. 158.
[3] Byrom, *Iron and Steel Inst. J.*, 1915, ii.
[4] Sears, *Cambridge Phil. Soc. Trans.* xxi. 105.
[5] G. I. Taylor and C. F. Elam, Bakerian Lecture, *Roy. Soc. Proc.* A, 1923, cii. 643.
[6] Wartenberg, *Zeitschr. f. Elektrochemie*, 1917.
[7] Rosenhain and Archbutt, *Roy. Soc. Proc.* A, 1919, xcvi. 55.

required to break the material in an ordinary test. In the case of the aluminium alloy, the facility with which such inter-crystalline fracture can be produced is closely correlated with the heat treatment and micro-structure. Treatment which renders this alloy entirely "equi-axed" in structure, with crystals having smooth boundaries, leads to rapid failure under continued loading; on the other hand, the same material treated so as to avoid the formation of regular crystals with smooth boundaries, can be rendered entirely immune against this type of fracture. In this alloy also it is possible to render the process of failure by inter-crystalline separation sufficiently rapid to make itself felt in an ordinary tensile test if this is made to extend over several hours. Thus a test-piece of the material in its most susceptible condition, if loaded at the ordinary rate, will require a stress of 24 tons per square inch to produce fracture; a load of only 13 tons per square inch, on the other hand, will produce fracture if allowed to act for 56 minutes. In the case of lead, both cast and wrought, somewhat similar phenomena have been observed, but owing to the softness of the metal only slight stresses can be applied, and fracture occurs only after a correspondingly long time. Brass in the soft (annealed) condition is subject to the same limitation—a fact which accounts for the common association of "season cracking" with cold-worked metal. In the case of very mild steel, on the other hand, a number of examples of failure by inter-crystalline fracture have been observed in cases where the material has been exposed to considerable stresses for a long period (in some cases over 12 years), and particularly where the steel has been maintained at a slightly raised temperature.

These phenomena, and a number of others associated with them, are readily explained by the amorphous cement theory. It is only necessary to recognise that while in many cases the inter-crystalline cement is so viscous that under ordinary rates of loading it is quite incapable of appreciable flow and therefore behaves like a hard, strong solid, yet under prolonged loading it can and does flow to an appreciable extent. In some cases this flow is extremely slow and may only become noticeable if the metal is kept at a high temperature for long periods of time under heavy stress. In other cases (brass and the aluminium alloy) flow at more rapid rates is possible. Some account must, however, be taken of the nature of the crystal boundaries themselves. Where these are jagged or irregular in outline, relative motion of the two crystals over one another, even if permitted by sufficient mobility of the "cement," cannot occur unless the stress is sufficiently high to allow the numerous minute projections to be sheared off or to be displaced by crystalline slip; on the other hand, where the boundaries are smooth and regular, approximating to plane surfaces, inter-crystalline slip and, ultimately, separation will be greatly facilitated. This application of the amorphous cement theory to the explanation of "season cracking" appears to offer the only rational view of the inner mechanism of such types of fracture which has yet been put forward. It has been somewhat hotly controverted, but the objections raised to it appear to be based upon a failure to realise that the properties of an under-cooled viscous liquid must vary, from metal to metal and from temperature to temperature, according to the relative position of the true melting-point.

§ (8) Tempering and Quenching.—The theory of the existence, around the boundary of every crystal, however small, of a layer of amorphous metal lends itself to a ready and entirely consistent explanation of a whole series of other phenomena. The most striking of these is the hardening and tempering of certain alloys (notably steel) as the result of quenching from a suitable temperature, followed, where necessary, by subsequent tempering. The phenomena in the case of steel are dealt with in detail elsewhere (see article on "The Iron-carbon Alloys"), so that they may be very briefly summarised here. Steels at high temperatures (above the upper critical point) are known to consist of a homogeneous solid solution of carbon or iron carbide in γ-iron. In pure carbon steels, no intensity of quenching yet attained has proved sufficient to retain the steel entirely in this condition after cooling, but the behaviour of steels containing nickel or manganese indicates that if the γ-iron solid solution could be retained down to the ordinary temperature it would not be very hard, and it would certainly be non-magnetic. Actually, severely quenched carbon steel contains only small areas of a constituent (austenite) corresponding to unchanged γ-iron. The remainder takes the form of martensite, which is intensely hard, and also magnetic. On the view of the nature of hardening, which is based on the amorphous cement theory, the γ-iron solid solution has undergone incipient decomposition during the rapid cooling process which occurs when steel is quenched, and this incipient decomposition has taken the form of the development of a very large number of extremely minute crystallites of both α-iron[1] and of cementite

[1] The fact that martensite contains material possessing the typical atomic spacing of α-iron has recently been demonstrated by X-ray methods by Westgren, *Iron and Steel Inst. J.*, 1921, I.

(iron carbide). But each of these minute crystallites will be surrounded by its envelope of amorphous iron, which is so highly viscous as to be in effect an intensely hard solid. If the newly-formed crystallites are sufficiently small and numerous, the resulting steel will contain a considerable proportion of amorphous metal, and its intense hardness is thereby readily explained in terms of the hardness—already postulated from other sources—of amorphous iron. At the same time, the other properties of the steel are readily accounted for. The presence of an immense number of micro-crystallites of α-iron accounts for the magnetic properties of hardened carbon steel. The α-iron of these crystals is, of course, magnetic, but its response to a magnetising (or demagnetising) field is very severely restricted by the extent to which the atoms of the minute α-crystallites are linked with the adjacent non-magnetic atoms of the amorphous cement. There is thus a considerable reluctance to become magnetised, and, once magnetised, a considerable resistance to becoming demagnetised. In this way the close correlation between magnetic and mechanical hardness is readily explained—an explanation which other theories of hardened steel have hitherto failed to provide. Further, the presence of micro-crystallites of iron-carbide serves to account for much of the chemical behaviour of hardened and tempered steel. It is not surprising to find that the two kinds of crystallites should display a tendency to become arranged in layers corresponding to the original cleavages of the pre-existing crystals of γ-iron, and such an arrangement would serve to account for the structure of interlaced needles or plates found in martensite. Slightly greater coalescence of the crystallites as the result of tempering accounts for the decreasing hardness produced by tempering at successively higher temperatures and also for the varying appearances found on etching tempered steels (troostite, sorbite, etc.). An interesting confirmation of the view, which is fundamental to the explanation of hardening on the amorphous cement theory, that the hardness of quenched steel and of cold-worked iron or mild steel is due to the same cause, viz. the presence of an appreciable amount of amorphous iron, has been obtained by Whiteley,[1] who has found that the gases evolved when hardened steel is dissolved in certain acids correspond very closely with those formed when strain-hardened iron or mild steel is treated in the same way.

The particular value of the theory of the nature of hardening indicated above is that it is directly applicable to any metal and is not dependent upon the peculiar properties of iron or carbon. This is now an essential feature of any theory of hardening, since a number of other alloys are known which undergo hardening in a manner so closely analogous to the behaviour of certain alloy steels that an identity of mechanism must be admitted. A typical example of such an alloy is that known as "duralumin," which contains about 95 per cent of aluminium, 3 to 4 per cent of copper, about 1 per cent of manganese, and about $\frac{1}{2}$ per cent of magnesium, a small amount of silicon being also a necessary ingredient. This alloy, when in the wrought condition, may be hardened by quenching it from a temperature near 500° C. Immediately after such quenching it is not hard—indeed, it is then softer than in the annealed and slowly cooled condition; gradual hardening, however, sets in after a few hours, and continues until an approximately final condition is reached in about four days. A number of other aluminium alloys are now known to exhibit similar phenomena, as well as certain alloys of lead. At first sight the analogy with steel is not very evident, but it becomes so if it is realised that in these alloys quenching can and does retain the metal in the soft, high-temperature state corresponding to that of the γ-iron solid solution of steel, much as can be done by quenching a manganese or a nickel steel. These alloy steels, however, if thus kept soft by quenching, can then be hardened by slight heating (tempering), and if it so happened that the ordinary temperature of the air were such as to produce extremely gradual tempering, then these alloy steels also would gradually harden if kept at the ordinary temperature after quenching. Artificial cooling would inhibit such a change and slight warming would accelerate it. The latter is precisely what occurs in the aluminium alloys; if kept at very low temperatures, age-hardening is inhibited, while it is accelerated by warming to 100° C. or even 200° C. for a short time. Now the cause of hardening in all alloys of this type has been clearly recognised in relation to the shape of their constitutional diagrams, and a principle applicable to all such cases can be stated as follows: hardening is due to the separation, in an extremely fine state of division, of a constituent which has been in solid solution at a higher temperature and which has first been retained in solid solution by rapid cooling, and is subsequently allowed to separate by some process of tempering, either at the ordinary temperature or at higher temperatures. The condition that such a process shall be possible is that a constituent must be present which is more soluble in the matrix metal at high temperatures than at low temperatures.

[1] Whiteley and Hallimond, *Iron and Steel Inst. J.*, Carnegie Scholarship Memoirs, 1918, ix.

§ (9) Solubility and Hardening.—The above principle covers the cases of all the alloys yet studied as well as that of steel. In the aluminium alloys, such compounds as magnesium silicide (Mg_2Si) and the compound $CuAl_2$ show distinctly greater solubility in solid aluminium at a temperature near 500° C. than at the ordinary temperature, while in the case of steel, iron carbide (Fe_3C) is very soluble in iron above 900° C., and is practically insoluble in it at the ordinary temperature. The main differences between these alloys and steel arise from the circumstance that while the solubilities of the compounds in aluminium decrease gradually with falling temperature, the solubility of carbide in iron falls suddenly to zero when iron undergoes its allotropic transformation. The consequence of this circumstance constitutes the second difference —that while in the aluminium alloys fairly rapid cooling entirely inhibits the separation of the second phase, in steel this separation cannot be entirely prevented—in other words, steel tempers itself to that slight extent even during the rapid cooling which occurs on quenching.

The close analogy between the hardening of steel and that of the alloys mentioned is of particular importance from the present point of view because it serves to show that any valid explanation of the source of hardness in hardened steel must also be applicable to these alloys. All theories which depend upon the special properties of iron in one or other of its allotropic forms must fail entirely on this ground. The view, however, that the minute particles or crystallites in which a dissolved substance separates from solid solution at a relatively low temperature must be surrounded by thin amorphous envelopes, is equally applicable to all metals, and furnishes a rational explanation for the apparently varied, but really similar, phenomena which are met in widely different materials.

With the exception of the above discussion of the theory of hardening in steel and other alloys, the whole of what has so far been said in regard to the behaviour of metals under plastic strain, fatigue, etc., has related to pure metals. This limitation has been observed in the first instance for the sake of simplifying the whole range of phenomena as far as possible, and in the second place because the experimental evidence upon which the views advanced above are based has been mainly obtained from the study of pure metals. While this is moderately satisfactory from the theoretical point of view, it is unfortunately quite unsatisfactory from the more practical standpoint, since the great majority of materials which are of any great practical importance are alloys of varying degrees of complexity. Fortunately, one whole class of alloys approximates very closely in its characteristics to those of a pure metal, and the observations made on pure metals are directly applicable to this type.

Broadly speaking, all alloys may be divided into two groups, according as they consist of (*a*) homogeneous solid solutions, or (*b*) of two or more distinct solid phases or micro-constituents. In many of the alloys of group (*b*), however, it must be remembered that one or all of the constituents are, as a rule, themselves saturated solid solutions. It has already been indicated that the crystals of a homogeneous solid solution behave in a manner which, to all appearances, is identical with that of crystals of a pure metal. Thus the phenomena of the formation of slip-bands as the result of plastic strain, and the phenomena of fatigue, are substantially the same.

§ (10) Solid Solutions.—There is, however, at least one very important experimental fact which requires explanation from the point of view of the relation of strength to micro-structure. This is the influence which the presence of an added element in solid solution exerts upon the mechanical properties of the metal. This is, in every case, a hardening and strengthening effect which is accompanied by a more or less marked decrease in ductility. In other words, although the actual phenomena of slip within the crystals of a solid solution exposed to severe stress appear to be very similar to those which occur in a pure metal, there is yet the very important difference that a higher stress is required to produce the phenomena. There is no obvious explanation for such a difference which can be found directly from microscopic examination, so that for an explanation we must look to such knowledge as we possess of the internal structure of the crystals themselves. The view of crystal structure which recent researches, particularly by means of the X-ray spectrometer, appear to have established is that of a regular arrangement of atoms upon some definite space-lattice corresponding to one of the possible arrangements compatible with the crystalline system to which the metal belongs. But, apart from the general shape or "scheme" of such a spacial arrangement, there also appears to be a particular size or a particular inter-atomic distance characteristic of the crystals of each material. This scale of the crystal structure is, no doubt, intimately related to what we term the atomic volume of the metal.

Upon this conception of the internal structure of a crystal it is possible to base a view as to the probable internal structure of a solid solution, and that view which, in the writer's opinion, appears to fit the facts most readily is that within the limits of "solid solubility" the crystals are built up of the

two kinds of atoms—those of the solvent metal and those of the solute—in an indiscriminate manner. If the natural crystalline system as well as the normal inter-atomic distance of the two metals were exactly the same, such a mixed structure could be built up out of the two kinds of atoms in any proportion—the two metals would be completely isomorphous, and would form a continuous series of solid solutions. Further, if the factors named were truly identical in the two metals, then also there would be no reason to anticipate that the mixed structure would exhibit any special properties other than those derived from a linear relationship with the properties of the two pure metals concerned. But in actual cases, where the two kinds of atoms necessarily differ in important respects, even if their atomic volumes are closely similar, such perfectly complete isomorphism can scarcely be anticipated. The fact that solid solutions of considerable concentration can be formed between two metals which are known to be very far from completely similar in regard to the factors in question shows that, up to a certain point, dissimilar atoms can be built up together upon the space-lattice arrangement characteristic of the predominating kind of atom. Where two metals are almost completely similar it may be possible to build up a mixed structure out of the atoms of both in any proportion, but the resulting structure is likely to exhibit properties which are not linear functions of those of the two component metals, because the whole inner structure will be materially affected as regards its internal cohesive forces, by the slightly imperfect "fit" of the two kinds of atoms into a single space-lattice system. The general effect of such a want of complete "fit," whether of actual size or of the field of cohesive forces, can best be regarded as producing something in the nature of a slight distortion of the whole space-lattice system. Such internal distortion corresponds, in a certain sense, with the existence of a system of internal stress. Probably the amount of any such distortion will be least for some particular, possibly symmetrical, grouping of the two kinds of atoms, and after prolonged "annealing" at a suitable temperature it seems probable that the two kinds of atoms will arrange themselves in such a manner, since it implies a minimum of internally-stored potential energy. It is this storage of energy as the result of internal distortion which, in the case of slightly dissimilar metals, must set a limit to the proportion in which atoms of a metal (B) can be built into the space-lattice of the solvent metal (A)—in other words, the limiting solid solubility of one of the metals in the other.

The effect which the slight internal distortion of the space-lattice arrangement of a crystal is likely to have upon its mechanical properties can be readily understood from what has been said above in regard to the micro-mechanism of plastic deformation and of yielding under stress. Ductility, we have learnt to recognise, is essentially a property of crystals which possess perfectly developed cleavage or gliding planes. The serious disturbance of the regular arrangement of the atoms in their space-lattice which occurs under plastic strain by the formation of amorphous metal, results, as we have seen, in the more or less complete destruction of ductility or plasticity. The system of well-developed gliding planes is interfered with and ultimately is obliterated for all practical purposes—while the metal becomes successively harder and more brittle. On this view it is evident that *any* disturbance of the perfectly regular arrangement of the atoms in a crystal must increase the hardness of the material by giving the crystal an increased resistance to slip on its gliding or cleavage planes. From this (somewhat geometrical) point of view, the effect of the introduction of slightly different atoms into a space-lattice system results in a slight distortion or "roughening" of the gliding planes, so that in the first place a higher stress is required to initiate slip and the total amount of slip which is possible without fracture becomes less—since movement on such slightly distorted "planes" must bring with it much greater dislocation of adjacent layers of atoms than in the case of a pure metal.

The above analysis of the internal structure of a solid solution therefore offers a very ready explanation of the fact that the successive addition of a second element entering into solid solution brings with it increasing hardness and strength, and after a time decreasing ductility or plasticity, and this sequence is that typically found in solid-solution alloy systems. There is, however, a further inference which, by its striking correspondence with observed facts, serves to strengthen the validity of the explanation here put forward. This may be realised by appreciating the fact that, the less perfect the "fit" of a given kind of atom into the space-lattice of the solvent metal, the lower will be the limiting concentration up to which a solid solution can be formed. At the same time, or, rather, for the same fundamental reason, the internal distortion of the space-lattice, and therefore of the cleavage or gliding planes of the metal, will be greatest with those atoms whose "fit" is least close, so that the hardening effect of a dissolved metal may be expected to be greatest in those cases where the limit of solid solubility is comparatively low. Where the limit of solid solubility is very low indeed—

so as to amount, in fact, to substantial insolubility—this inference cannot be verified, but in numerous cases where there is an appreciable but still limited range of solid solubility the inference serves to explain, in a striking and satisfactory manner, the relative hardening effects of various metals upon one another. Thus, the limit of solid solubility of tin in copper is very much lower than that of zinc, and the hardening effects are, roughly, in the inverse proportion. The same comparison holds good in regard to the effect of copper and zinc on aluminium, and to a still more striking degree in the comparison of the effect of carbon and nickel on iron.

The analysis of the conditions affecting slip and the formation of amorphous metal in alloys consisting of two or more micro-constituents is a matter of much greater difficulty and can only be attempted, in the present state of our knowledge, in somewhat vague and general terms. Here the constituents themselves are, as a rule, saturated solid solutions whose more complex internal character has just been discussed, and in addition the simultaneous behaviour of different crystals having widely different properties must be considered as affecting the distribution of stress and of deformation among the various constituents. There is, also, the further complication that the relative size and arrangement of the constituents affects the physical properties of the material as a whole, since it determines not only the extent of crystal boundary and the amount of amorphous material present in these boundaries, but also the degree to which the movements of the various constituents are linked together. The problem, it will be seen, is thus a complicated one whose factors vary widely in different structures.

In the case of an alloy consisting of a relatively soft matrix in which comparatively few, small, hard crystals of a second phase are embedded, it is evident that the physical properties and the general behaviour will be very similar to those of the pure metal; even a few small scattered crystals of a harder kind will, however, serve to stiffen the material as a whole, since the harder crystals serve to key or link together groups of differently oriented crystals of the matrix metal and thus enable them to offer increased resistance to plastic slip. The more finely divided these hard particles, the greater will be their effect, and this is merely one example of the universal rule which is applicable to duplex or complex alloys even more strongly than to pure metals or solid solutions, that in regard to most physical properties, a fine structure is advantageous.

In many duplex alloys, one of the constituents is very hard but brittle, while the other (predominating) one is soft and ductile. In such a case it is found that the material as a whole will possess a very considerable degree of ductility, combined with an increasing degree of strength and hardness, so long as there is enough of the ductile constituent present to encase the hard, brittle constituent. So soon, however, as the hard, brittle constituent is present in sufficient quantity to form linked-up elements of the structure, such as a network surrounding the ductile constituent, the material as a whole loses its ductility and begins to assume the properties of the hard, brittle body. Particularly where brittle material is present in the form of fine particles or of thin plates embedded in a ductile material, the "natural" brittleness of the hard body is to a considerable extent masked. The adjacent ductile material appears to protect the brittle body from the incidence of forces capable of causing its fracture, and even to support it to such an extent that it undergoes a certain amount of plastic deformation without fracture. In its turn the hard material "stiffens" the adjacent crystals of the ductile body. This action is, of course, more perfectly developed the closer and more intimate the juxtaposition of the two phases; it is for this reason that quenched and tempered steels can be obtained in a state exhibiting very remarkable combinations of strength and ductility; in this condition they exhibit an extraordinarily minute micro-structure in which soft "ferrite" and hard "carbide" are intermingled.

W. R.

METALS, THERMAL AND MECHANICAL TREATMENT OF

Apart from the purely metallurgical processes employed in the extraction and purification of metals, both thermal and mechanical treatment may be regarded as beginning with the operations of melting and casting.

§ (1) Melting.—Melting may be properly regarded as purely a thermal operation and, from the physical point of view, it is a very simple one, the object being to obtain the desired quantity of metal, of the correct composition, in the liquid state and at a temperature suitable for casting. The temperatures entailed must, of course, vary very widely according to the metal to be dealt with. Among those commonly employed steel probably demands the highest temperatures. The melting-point of pure iron is now known to lie in the neighbourhood of 1500° C., but to obtain liquid steel in a suitable condition for manipulation much higher temperatures are employed, ranging up to 1650° C. and even 1700° C. Probably next in order of

refractoriness come nickel and its alloys, requiring temperatures up to 1500° C. It is, however, a notable fact that certain of the intermetallic compounds formed by nickel and aluminium, and probably also by nickel with both aluminium and copper together, have very high melting-points indeed. More usual types of alloys, such as those of copper, rarely demand temperatures higher than 1100° C. or 1200° C., and there are whole series of alloys, such as those of aluminium, of lead, and of tin, which require very much lower temperatures. On the other hand, there are certain metals, particularly tungsten and molybdenum, which require such extreme temperatures for their fusion that it has not yet proved possible to melt them in the mass, the main difficulty residing in finding an adequately refractory container in which to melt them. In some similar cases, however, this type of difficulty has been overcome by using the material to be melted as its own container. For this purpose a heap of the material in powder form is placed in a water-cooled box or container, and intense electric heating is applied within the mass of the material. A portion then melts and is retained by the cold and solid exterior portions. Treatment of tungsten and molybdenum by such a method, however, is not as yet an industrial process. Platinum and its alloys, although requiring fairly high temperatures, can be readily melted in containers made of lime or magnesia, and therefore present relatively little difficulty.

The furnaces used for melting metals vary very widely in accordance with the temperatures to be employed, and also in relation to the quantity of metal to be melted at one time. By far the most usual type of furnace for the industrial melting of metals even at the present day is still nothing more than a coke fire in which a fireclay crucible is heated. Gas-fired crucible furnaces are gradually displacing these cruder coke-fired "holes," and in the case of steel crucible melting, gas furnaces are now almost exclusively used, as the application of the regenerative principle enormously facilitates the economical attainment of the high temperatures involved.

Where the quantity of metal to be melted is small, and particularly if accurate control of composition and immunity from contamination are essential, melting in crucibles offers many advantages. It is, however, relatively a costly process, and melting in open-hearth furnaces of various types is employed where possible. In these furnaces the metal lies in a bath formed in the floor or "hearth" of the furnace, and the flame—whether of gas, oil, or even pulverised coal or coke—plays over the surface of the bath of metal. In steel-melting, where metallurgical refining accompanies the process of melting for casting purposes, the open hearth is particularly advantageous, and this type of furnace has been developed to very large sizes, capable of dealing with from 80 to 100 tons of steel in one charge. These large furnaces are sometimes so constructed as to be capable of being tilted for the purpose of pouring out the molten charge, although more usually the metal is drawn off through a "tap-hole" pierced in the walls of the bath. Furnaces of very much smaller size, but operating on the same principle of the open bath of molten metal, are also widely used for other metals.

The melting operation in practice very rarely consists in the mere melting down of previously prepared metal. Even where there is no metallurgical refining process involved, the melting process is generally also one of mixing or alloying. The mixing of two or more metals may be carried out in several ways, *i.e.* a solid metal may be thrown into a molten one, or the molten metal may be poured on to solid metal contained in another vessel, or two portions of molten metal may be poured one into the other. As a rule, it is important to select that method which involves the least excessive heating of any of the metals concerned. Usually, alloys of known composition, but much "richer" than those finally aimed at, are previously prepared. This preliminary alloying has several important advantages, since it is found that these "rich" alloys are nearly always brittle and can therefore be readily reduced to small lumps or powder, which greatly facilitates weighing out the correct proportions needed. Equally important is the circumstance that as a rule these "rich" alloys are considerably more fusible than, at all events, the less fusible of their components, which again facilitates the operation. As an example we may take the case of the preparation of an alloy of aluminium with, say, 4 per cent of copper. The aluminium, which constitutes the great bulk of the alloy, is first melted. If, now, the copper were added as pure metal, it would require a very high temperature to induce the copper to dissolve in the aluminium, and the whole of the metal would thus have to be overheated. To avoid this, an alloy containing about equal proportions of copper and aluminium is first prepared. This is extremely brittle and is therefore easy to weigh out in the exact proportion. Further, this alloy melts completely at a temperature below 600° C., as compared with 1065° C. of copper (containing oxygen).

The operation of alloying requires fairly vigorous stirring in order to secure good mixing, but want of uniformity in alloys cannot often be ascribed to this source.

Much weight is also sometimes attached to the order in which it is supposed to be necessary to introduce the various metals of an alloy. Broadly speaking, this contention may be dismissed as being without scientific (or practical) foundation. A molten alloy is nothing more nor less than a liquid solution of the components in one another, and—provided that there is no precipitation—it follows that the final equilibrium existing in such a solution must be the same however it may be produced. There are, accordingly, only a few special cases in which the order of alloying can play any important part. The question of the maximum temperature required to bring any particular ingredient into solution is a factor to which we have already referred, but there are a few others. Thus certain metals are relatively volatile (zinc, cadmium, and lead), and these are apt to be partially lost if introduced early in the operation or if unduly heated. Then, again, it must be borne in mind that during melting the metal is exposed to chemical reaction with its surroundings, whether solid, liquid, or gaseous. Some metals are much more readily affected in this way than others. Thus magnesium is apt to combine with oxygen or nitrogen or both, and is therefore best introduced just before casting. On the other hand, some metals and metalloids (such as phosphorus) are deliberately introduced into alloys for the purpose of freeing them from some undesired contamination, such as oxides. Here again it is eminently desirable to introduce the deoxidant at the proper time, since otherwise the alloy may become re-oxidised before it is cast. The special nature of these exceptions will serve to show that the process of alloying in itself is independent of the order in which the metals are dissolved in one another.

In all melting and casting operations it is necessary to "superheat" the metal, *i.e.* to take it to a temperature considerably above that of complete melting. The question arises to what extent this is permissible. There is a widespread idea that if the metal—whatever its nature—is made unduly hot, it is "burnt" and suffers in some way in its ultimate qualities. In special cases there can be no doubt that excessive superheating is injurious. Thus alloys containing any notable proportion of zinc give off dense fumes if heated much above their melting-point, and such loss of zinc is obviously undesirable. In all cases, indeed, oxidation, and the absorption of gases generally, increases with rising temperature, while chemical action with the containing walls, and with any slag or flux that may be used, also increases. It is, therefore, evidently desirable not to superheat metal unduly. At the same time, many alloys, just above their melting-point, appear to be somewhat viscous or "thick," and good mixing, and even good casting, demands a higher temperature. It should also be stated that careful experiments have shown that, in some cases at all events, harm is done to metal when superheated only if it is disturbed (*i.e.* stirred or poured) while excessively hot, but that, if it is left quiescent and allowed to cool down before being manipulated, little if any harm is done. On the other hand, the maximum temperature to which molten metal is raised may affect the subsequent crystallisation, but this connection has yet to be established.

§ (2) Casting. — The operation of casting (sometimes called "pouring" or "teeming") must be regarded as combining thermal with mechanical treatment; from the thermal point of view it is mainly concerned with the effect upon the metal of cooling it through the solidification range at various rates, while mechanically casting is the first of the operations employed for bringing the metal into the desired shape or form—the mechanical force employed being the hydrostatic pressure of the liquid metal itself. For the purpose of securing a piece of metal of any desired shape, in fact, casting presents at once the simplest and the most perfect of processes. Recently the so-called "dye-casting" processes have been very considerably developed, and by these it is possible to obtain castings having such accurate shapes that for many purposes even machining or finishing can be avoided. This, however, is only attainable with certain special alloys which it is possible to force, under considerable pressure, into strong and accurately made metal moulds. Even where such extreme accuracy of shape and size is not obtained, however, the casting can always be brought very nearly to the desired dimensions, and the question therefore arises why castings are not more extensively or even exclusively used for engineering purposes. The answer lies in the fact that in a great many materials, and particularly in the better qualities of steel, it is not possible to obtain from the cast metal the best possible physical properties which the material can be made to develop. The further consideration of the casting process will serve to show the reasons for this difficulty, but it should be pointed out that with improvements in metallurgical knowledge and practice the quality of castings is constantly improving, and that accordingly their use is extending. Ultimately it may prove to be possible to overcome the objections to castings in all or nearly all cases. At present, however, the operations of mechanical treatment, in particular such as forging, rolling, stamping, etc., serve to bring the metal into a better condition

and also to eliminate, at all events, all coarsely defective material.

All casting operations, therefore, must be divided into two distinct groups, according as the resulting casting is to be used in that form or is to serve as the basis for forging, rolling, etc. In the former case the liquid metal is poured into a mould having the shape of the article to be produced, while in the latter the mould is shaped to produce the ingot or slab, as the case may be, from which the final product is to be formed. These differences bring about material modifications in the conditions governing the casting operation, but, none the less, similar considerations govern it in all cases.

Considering first the production of shaped castings, the first condition which must be satisfied is that the metal must be sufficiently fluid to fill the mould readily and completely. The exact degree of "superheat" required to meet this condition will vary with the size and shape of the casting and with the nature of the moulds employed. In small castings of simple shape and uniform thickness, no very hot metal is required, even if metal moulds or "chills" are used. Larger and more intricate castings are generally moulded in sand, and such sand moulds may be either "dry" or "green." In both classes the sand with which the mould is made is distinctly damp; where the casting is made in "green-sand," the mould has not been seriously dried, and the molten metal as it enters must volatilise the water which is still present. Provision must be made for the easy escape of the resulting steam, and the heat absorbed by the evaporation of the water must also be provided from the metal. In "dry-sand" casting the moulds are thoroughly dried or even baked before casting; there can be no doubt as to the greater desirability of this process, and its use is only limited by the increased time and cost entailed by the drying operations. Broadly speaking, it may be said for both kinds of castings that the best casting temperature, in nearly every case, is the lowest at which the metal can be relied upon to fill the mould thoroughly, and this is higher in "green" sand than in dry. Any temperature higher than this is most undesirable, for a variety of reasons, but it is decidedly less so in most kinds of shaped castings than in the production of slabs or ingots. Even in shaped castings, however, the main objection to high casting temperatures applies with great force; this is the fact that, by using unduly hot metal, the mould itself is very considerably heated, and the rate at which the metal cools through the freezing range of the alloy is therefore very considerably reduced. Now, in almost every metal, the higher the rate at which solidification takes place, the finer the "grain" of the resulting structure and the better the physical properties. So much so is this the case that a thick and a thin portion of the same casting will give widely different results under mechanical tests, simply because the thin portions have cooled much more rapidly than the thick. Castings poured at too high a temperature, therefore, generally show a coarse micro-structure and are weak mechanically.

In the production of slabs and ingots for forging or rolling, the conditions are somewhat different. These castings are always made in metal ("chill") moulds, and there is no question of requiring the metal to flow through narrow and intricate passages. On the other hand, the mass of metal to be dealt with in a single piece is very much greater. Here also the condition that the lowest possible temperature should be employed in order to secure the most rapid available rate of cooling through the freezing range applies very strongly, and as a rule lower pouring temperatures can be used in the production of slabs and ingots than for shaped castings. On the other hand, it is often necessary that the surfaces of such slabs and ingots should be as perfect as possible, since defects in these surfaces are apt to produce more serious defects in the rolled material at later stages. If the metal is poured into such moulds at too low a temperature, however, it is apt to form small portions of solid crust where it is cooled by contact with the walls of the mould or by exposure to the air. Fresh liquid metal falling upon these little crusts may then be insufficiently hot to bring about local remelting and fusion, with the result that defects are produced, known as "cold shuts," where adjacent portions of the metal are not really properly joined. These and other defects, mainly affecting the surface of the ingot or slab, are liable to result from too low a casting temperature.

In the case of slab and ingot moulds, however, another consideration arises in regard to the rate at which metal is poured into them, as well as in regard to the temperature of the metal. We may begin by considering the imaginary extreme case in which the entire mould is instantaneously filled with molten metal, as indicated in the diagram, *Fig.* 1 (*a*). Since the metal is mainly cooled by contact with the walls of the mould, the first portion to solidify will take the shape of the shaded area in *Fig.* 1 (*b*). Thermal contraction due to cooling of both liquid and solid, as well as such contraction as frequently accompanies solidification, will produce a diminution of the total volume of the metal, with the result that the level of the residual liquid metal has begun to

fall, as indicated in *Fig.* 1 (*b*). This process will continue in successive stages, as shown in *Fig.* 1 (*c*) and (*d*), leading, finally, to the formation of a deep central contraction cavity or "pipe." If the ingot or slab is to be rolled, it is evident that, in order to obtain sound material, the whole of the upper portion in which the "pipe" occurs must be cut away and remelted. In order to avoid this costly expedient, efforts are made to prevent the formation of the pipe. These usually take the form — in non-ferrous metals, at all events — of endeavouring to pour in additional liquid metal, and thus to maintain the level at or near the top of the mould. This, however, is only partially successful, as the metal in the mould in the first instance rapidly forms a surface skin, partly by solidification and partly by oxidation, with the result that the metal subsequently added does not completely join with that already present. If an ingot poured in this way is afterwards cut through and polished and etched, the outline of what would have been the contraction cavity can generally be clearly seen, although the cavity itself is filled by a plug, or several successive plugs, of metal; and for many purposes, such as extrusion (see below), an ingot having this structure is unsatisfactory. In other cases, such as steel, any such "following up" operation in casting is impracticable, and entirely different devices are employed. For large ingots particularly, one of the simplest of these is the provision of what is known as a "feeder head." This is simply an extension of the ingot mould upwards, in the manner indicated in *Fig.* 2 at H, H. This extension is, however, constructed of firebrick or other material which does not allow the molten metal to cool so quickly as that in the mould proper. The liquid metal in the "head" therefore serves as a reservoir from which the ingot proper can draw a supply as cooling and contraction goes on. The open-air surface of the metal in the feeder head, however, is apt to solidify and thus to hinder the downward flow or "feeding," and to avoid this Hadfield [1] has proposed that this surface should be strongly heated—in the case of steel by means of coke and a powerful air-blast, but an oxy-acetylene flame or the electric arc could equally be used. Whatever metal remains in the feeder head when the whole has solidified must, of course, be rejected, but as a rule all that is left there is a thin shell.

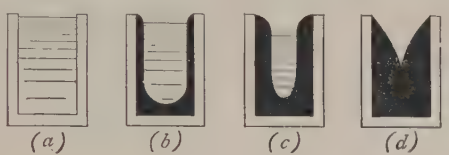

FIG. 1.

Another method of avoiding serious contraction cavities in a solidifying slab or ingot is, however, available, more particularly for smaller masses of metal. Consideration of *Fig.* 1 will show at once that the volume of the contraction cavity, for a given alloy having a definite ratio of contraction from hot liquid to cold solid, must be proportional to the total amount of liquid metal present in the ingot mould. We have supposed, for simplicity, that the mould was instantaneously filled with liquid metal, so that no freezing took place while the mould was being filled. On the other hand, we might suppose that the same mould was filled in a very large number of stages, only a little liquid metal being poured in each time and this being allowed to solidify before more was added. Since the total volume of liquid present each time is small, the resulting contraction cavity must be small also, and we should have filled our mould without incurring the formation of a large pipe. In practice it would, of course, be impossible to proceed in this manner, since we should have bad joints or "cold shuts" between each successive layer. It is, however, perfectly possible to approximate to this method of filling an ingot or slab mould by so timing the rate at which molten metal is allowed to run into it that there is never more than a small amount of liquid in the mould at one time—the molten metal is run in at as nearly as possible the rate at which it solidifies, thus merely maintaining a layer—perhaps a few inches thick—of molten metal on top of the solid already formed. Careful, steady pouring — generally by mechanical aids — is essential, as well as accurate control of the rate of flow, otherwise "cold shuts" and surface defects make their appearance, but the method is perfectly practicable and successful.

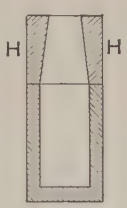

FIG. 2.

Unsoundness in castings, whether shaped or ingots, is not always due to the formation of contraction cavities, but may also arise from the liberation, during freezing, of gases present in the molten metal. This phenomenon is often met with in the case of aluminium and its alloys, and to a still more striking extent if attempts are made to obtain castings of metallic magnesium if this metal has been melted in a manner which allows it to take up hydrogen gas. In the majority of metals,

[1] Hadfield and Burgess, "Sound Steel Ingots and Rails," *Iron and Steel Inst. J.*, 1915, i.

however, although there is probably always some liberation of gas during the freezing process, the resulting defects can be minimised by avoiding all overheating of the molten metal and reducing, as far as possible, the exposure of the hot molten metal to injurious gaseous atmospheres. A case of peculiar difficulty and importance is, however, presented by steel. In the melting and refining of steel a chemical reaction takes place between the carbon present in the original metal and oxygen which is present in the molten steel as iron oxide. This reaction results in the formation of carbon monoxide gas, and during the later stages of steel-melting in an open-hearth furnace, for instance, the metal is seen to "boil" as the gas escapes. If this reaction is completely finished before the steel is poured into the ingot moulds, no further trouble arises: the steel is said to be "dead-melted," and lies quiescent in the moulds. But if the reaction is still incomplete, the evolution of gas continues and the steel tends to rise in the mould, much as aerated lemonade "rises" when poured into a glass. This tendency to rise has been utilised in order to counteract the formation of the natural shrinkage cavity which would otherwise be formed as a central pipe, and in that case the shrinkage of the steel makes its appearance in the form of a large number of blow-holes or gas cavities lying near the peripheral parts of the ingot. It has been thought that such relatively small cavities are harmless, as they may be expected to weld up during forging and rolling, but there is good reason to doubt whether this occurs, and modern practice demands really sound, "dead-melted" steel. The continuance of the reaction between iron oxide and carbon in the steel can, however, be readily arrested by adding to the steel, either just before it is taken from the furnace or while it is in the ladle, some powerful deoxidant which rapidly removes all the iron oxide present, replacing it by an oxide which is not capable of reduction by carbon. Both silicon and manganese act in this manner, but the most powerful agent for the purpose is aluminium. This rapidly reduces all iron oxide and replaces it by alumina, which is unattacked by carbon at steel-melting temperatures.

In connection with the production of truly sound ingots, several special processes have been introduced which seek to secure the desired end by mechanical means. The first of these is the Whitworth "fluid compression" process, in which the liquid metal is poured into a closed ingot mould having one movable side. To this side intense hydraulic pressure is applied in a suitable press, with the idea that under a high hydrostatic pressure any contraction cavities or gas blow-holes which might otherwise form in the steel would be immediately closed up or filled. This no doubt occurs so long as there is enough liquid metal present to allow the side of the mould to produce large hydrostatic pressure. So soon, however, as enough metal has solidified to form a shell or crust which can resist the pressure applied to the movable side of the mould, the remainder of the metal must solidify under ordinary pressure and, what is worse, in a closed space in which a particularly unfavourable type of cavity is likely to be formed. Much sounder, from the physical point of view, is the Harmet compression process. Here, by powerful hydraulic presses, the solidifying ingot is forced upwards into a conically tapering mould. The ingot is thus exposed to compression which is powerful enough to squeeze the last portions of liquid out at the top of the mass. The result is highly satisfactory, but the cost of the process makes it impossible to apply it except in special cases.

§ (3) Segregation.—Beyond the phenomena arising from contraction, solidifying masses of metal, and particularly of alloys, are subject to another type of internal action which also militates against their homogeneity and soundness. This is the tendency, very marked in some cases, for the segregation of various constituents in different regions of an ingot. The causes and mechanism of such segregation are not, as yet, fully understood, although it is evident that differences of fusibility in the various solutions which are present in a metal must affect the arrangements of the constituents in any large mass which is cooled somewhat slowly. Thus, if there is a separation of primary crystals which are to a considerable extent "pure," *i.e.* consist of one primary constituent more or less free from dissolved elements and impurities, then the residual liquid, after a certain amount of solidification has taken place, must necessarily be richer in dissolved elements or impurities than the crystals first formed. In these circumstances we should expect to find that the central portions of a large ingot, which are the last to solidify, would contain the highest proportion of dissolved elements and impurities. In the case of steel ingots of considerable size, where solidification is unavoidably slow, such a state of affairs is frequently encountered; just below a "pipe" particularly, there is frequently a region containing a strongly marked segregate, rich in carbon and generally also in sulphur, silicon, and manganese. By suitable design of the moulds and regulation of the rate of teeming (or casting), the formation of these segregated areas can be considerably restricted, and their injurious effects

can then be completely eliminated by rejecting (or "cropping") the upper portion of the ingot as well as a small portion from the base. For purposes where the highest quality is required, this cropping sometimes involves the rejection, at the outset, of nearly one-half of the mass of the ingot.

Apart, however, from these actions, which are to some extent dependent upon the order in which the various constituents undergo solidification, there is an entirely different type of action which occurs in certain cases, where it is sometimes known by the rather unsatisfactory term "liquation." This has been observed with particular care in the case of ingots of the alloys of precious metals, since it tends to interfere with the production of ingots of sufficient uniformity to serve as standards for assay purposes. Similar phenomena have, however, been observed in other alloys, such as those of aluminium with zinc and copper. In the case of gold-silver alloys rich in gold, and in the corresponding case of the aluminium alloys rich in that metal, one would, from the point of view of order of solidification, expect to find the central portions of the ingots appreciably richer in silver or in copper and zinc respectively. Actually, the contrary is found to be the case, although only to a small extent (usually a fraction of one per cent). This only occurs, however, to any appreciable extent in the case of relatively small ingots which have been cast in "chill" moulds. The whole matter has not been studied sufficiently exhaustively to allow of a complete explanation, but it is evident that the formation of a steep temperature gradient within the metal just prior to solidification is essential for the production of the phenomenon. It may therefore be suggested that, in the liquid metal where this steep temperature gradient exists, a change of concentration occurs tending to equalise the osmotic pressure of the dissolved substances in adjacent portions at different temperatures. This would lead to a concentration gradient in the opposite sense to the temperature gradient being set up, and such an action would bring about the kind of segregation which is found in such cases. There is, however, as yet no experimental evidence that such a concentration gradient can be set up in a metallic solution, and the fact that many dissolved elements do not "liquate" appears to indicate that there must be other conditions which affect the formation of such a gradient.

Apart from all questions of segregation, there are very considerable differences in structure and physical properties between the outer and inner portions of a casting such as an ingot. Particularly where a "chill" mould has been used, the outer portion shows what is known as a "chill" structure, consisting of elongated crystals radiating inwards at right angles to the surface of the mould. The inner portions of the ingot, on the other hand, exhibit a structure consisting of crystals approximately of equal dimensions in all directions—usually called "equi-axed." The manner in which both types of crystal are formed is discussed elsewhere (see article on "Metals and Alloys, Micro-structure of"). For the present purpose we are mainly concerned with the fact that the material possessing these differing structures also differs to some extent in physical properties, and it becomes desirable to equalise these as far as possible, even for forging and rolling purposes. Where a casting is to be used without mechanical working, there is the further consideration that, owing to the fact that the external and thinner portions of the casting solidify before the interior and thicker portions, severe internal stresses due to thermal contraction are liable to be present: castings, in fact, not infrequently crack during or after cooling in consequence of the severity of such stresses. Both these defects can be remedied, more or less completely, by reheating or "annealing" the casting in a suitable manner. As far as the removal of internal stresses is concerned, this applies to castings of all metals; by heating them to a temperature high enough to allow the material to adjust itself slightly under existing internal stresses, and subsequently cooling at a rate sufficiently slow to avoid the introduction of new contraction stresses, this result is accomplished. The refinement and equalisation of the internal crystalline structure, however, is a much more difficult matter. In many metals, and particularly in those which do not pass through any allotropic or critical changes on cooling, it appears to be very difficult, if not impossible, to bring about any rearrangement of internal structure in an unwrought casting, and in that case the structure once impressed upon the material during solidification remains with it until it is remelted.[1] To some extent this is true of steel, and applies even after the application of a large amount of mechanical work. But it is true in that case only to the limited extent that the original crystal structure of the ingot leaves traces in the final structure of the steel which can only be eliminated—if at all—with extreme difficulty. Thus the banded markings seen on a polished and etched cross-section of a steel rail or a boiler plate, when cut longitudinally,

[1] Ewing and Rosenhain, *Roy. Soc. Phil. Trans.* A, 1900, "The Crystalline Structure of Metals, Second Paper"; Carpenter and Elam, "Recrystallization and Crystal Growth," *Inst. of Metals J.*, 1920, ii.

are the lineal descendants or representatives of the dendritic cores of the primary crystals formed when the ingot solidified. This, however, arises solely from the fact that some of the dissolved impurities, which are pushed into the outer regions of the original dendrites during freezing, only diffuse with extreme slowness, so that—even when the steel has been repeatedly recrystallised in the course of thermal and mechanical treatment—they retain their original relative position in the mass, their shape being merely changed in conformity with the change of shape which has been imposed upon the entire ingot.

Leaving aside this special feature, however, the internal structure of a metal such as steel, which passes through critical changes on heating and cooling, can be changed and refined by suitable heat treatment. The original coarse crystals can be broken up into many smaller ones, while the distribution of non-dissolved impurities can be advantageously altered. In regard to the latter type of change, the effect of annealing on the distribution of sulphides in steel castings may be instanced. In the condition as cast, these sulphides are apt to lie in films in the crystal boundaries, where they affect the strength of the metal most injuriously. When the casting is properly annealed, these films tend to contract into detached globules, presumably under the action of surface tension, and in this latter form are much less injurious.

§ (4) Mechanical Processes.—Returning to the consideration of ingots, slabs, etc., we have next to consider the mechanical processes by which they are to be brought into the desired shape and condition. The operations employed must necessarily vary not only in accordance with the nature of the metal, but also according to the character of the final product to be obtained. Long objects, particularly if of small diameter or of flat section, such as plates, sheets, rods, etc., are always produced by the process of rolling, which may be applied to the metal when either hot or cold. Still thinner sections, such as thin rod or wire, are usually produced by the process of "cold-drawing." On the other hand, shapes of a more varied character are produced by forging, pressing, and stamping, while in many cases combinations of these processes are employed, *i.e.* a rolled bar or sheet is used as the raw material for a small forging or stamping. The details and technique of these numerous and varied operations cannot be considered here, although each of them offers interesting examples of the application of physical principles. We can only consider briefly the more important operations, which include forging under the press and the hammer, rolling hot and cold, and cold-drawing.

§ (5) Forging.—The forging of iron and steel is always carried out at a bright-red heat, ranging between 1200° C. and 800° C., although these limits are sometimes exceeded in both directions. At higher temperatures not only is the metal likely to be injured, but it is also inconveniently soft for manipulation, while at unduly low temperatures the metal is so stiff and hard that even the most powerful presses and hammers cannot mould it readily. The process consists in squeezing the plastic mass of steel into a shape as near as possible to that desired for the finished object, due allowance being made for the removal, by machining, of the rough surface. Where large masses of steel have to be dealt with in this way, extremely powerful appliances are required. Great hydraulic presses are installed for handling such forgings as those used in the manufacture of large guns, ships' propeller shafts, etc.; the largest of these presses are capable of exerting a thrust of 10,000 tons, but are none the less capable of accurately controlled movement. For these very large masses of metal and the great forces required for shaping them, the hydraulic press is practically the only available appliance. For smaller work, however, the power hammer (usually the steam hammer) is also used. These hammers, however, cannot be made conveniently large enough for the heaviest work. It is also found that the shock with which they strike their work is rapidly injurious to surrounding buildings and machinery. Without entering further into the long-debated question of the relative merits of press and hammer for forging, it is interesting to inquire whether the manner in which forging is done exerts any important influence on the quality of the metal. This appears to depend upon the size and weight of the hammer used. A relatively light blow acts mainly upon the metal at or near the surface which has been struck, so that if a heavy piece is forged under a hammer of moderate power the outer regions of the piece receive more effective treatment than the interior, and a heterogeneity of structure between the interior and the exterior may be set up. If the blow of the hammer is heavy enough to affect the whole thickness of the forging, on the other hand, differences of that kind cannot arise. The question, however, still remains whether there is any specific effect due to "shock," *i.e.* to rapidly applied work as compared with the relatively slowly applied work of the press. At ordinary temperatures in iron and steel there does appear to be a distinct difference in the mode of internal deformation which is produced (see article on "Metals, The Relations of Strain and

Structure"), but whether this difference also occurs at a red heat has not yet been ascertained.

With regard to the manner in which metal adapts itself to changes of shape under the hammer or press, it is important to note in the first place that in these forging operations there is comparatively little constraint upon the metal, which can flow away in almost any direction equally. Thus while rolling, for example, produces extension mainly in a single direction, forging tends to squeeze the material out in all directions. Thus a slab of metal, for example, measuring to begin with 10 inches square by 2 inches thick, can be rolled out to a length of 50 inches and a thickness of 0·04 inch without increasing its width to much more than 10·5 inches. By forging, on the other hand, it is possible to convert such a slab into a square piece measuring 15 inches square with a thickness just under 0·9 inch.

§ (6) Rolling.—We have next to consider the process of rolling, by which by far the greatest amount of metal is manipulated in the metal-working industries. The process would, at first sight, appear to be a simple one, and some of the appliances used in it are decidedly rough and simple. On the other hand, where highly finished products are required, there can be no doubt that rolling requires not only mechanically perfect appliances, but also a considerable degree of technical knowledge and skill. In its simplest form, the rolling-mill consists of two "rolls" or rollers, generally made of iron or steel, which can be set parallel to one another and at any desired (small) distance apart, and these rolls are driven at a suitable speed by some powerful motor, such as a steam-engine or an electric motor. In the largest mills used in steel-works the rolls themselves may be as much as 18 feet wide and 40 inches in diameter, while the engine driving them may require as much as 25,000 horse-power. At the other extreme we have the jeweller's small finishing rolls, which can be easily turned by hand.

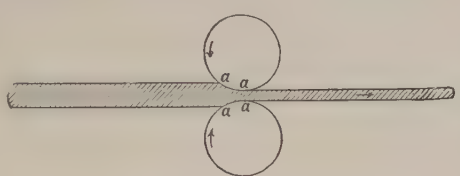

Fig. 3.

The manner in which metal undergoes reduction by passing through a pair of rolls is indicated diagrammatically in *Fig.* 3. There it will be seen that the separation of the rolls is somewhat less than the thickness of the metal before its passage. The metal is held by the rolls in a powerful grip due to the "arcs of contact" (a, a in the figure), and as the rolls revolve they carry the metal forward and force it through the opening between them. This implies that during its passage along the arc (a, a) the metal is exposed in the first place to powerful normal pressure tending to squeeze it out in much the same way as the pressure of the jaws of a forging press; in the second place, however, there is a strong tangential force tending to pull the metal forward with the revolving rolls, and it is this tangential force which directs the flow of the metal forward in the direction of rolling. The power required for this operation must, of course, vary enormously with the character of the metal under treatment, which may be either hot and relatively soft (hot-rolling) or cold and relatively stiff (cold-rolling). The power must also depend upon what is known as the "pass" employed, *i.e.* the amount of reduction in thickness which is applied in a single passage through the rolls. The selection of this ratio of reduction is a most important factor in rolling practice, and it varies very widely. As a rule, however, it is found desirable—particularly in hot-rolling—to carry out the reduction of thickness in the fewest possible number of passes, since this is not only economical of time in the rolling-mill, but is distinctly beneficial to the metal treated, as it appears to secure more uniform flow throughout the thickness of the sheet or bar. Apart from these factors, however, there is another of a much less obvious nature which also has an important effect on the power required to drive a rolling-mill. This resides in the diameter of the rolls themselves—the larger the roll the greater the power required. This arises primarily from the fact that the arc of contact (a, a in the figure) becomes much longer with increasing diameter of roll. If the pressure per square inch required to bring about a given reduction of thickness in the metal is the same, the total pressure which must be applied through the rolls must increase as the area of contact increases, and this conclusion is fully borne out by practice.

Another important consideration in connection with all rolling-mill operations arises from the fact that the pressures which are used are necessarily so high that the rolls themselves, and the stands or "housings" in which they run, cannot be regarded as practically rigid; allowance must be made for the elastic deflection or deformation, particularly of the rolls themselves. It follows, to begin with, that the thickness of the resulting sheet, for instance, is always greater than the apparent width apart of the rolls if the latter

is measured when the rolls are idle. The sheet itself, of course, also undergoes elastic as well as plastic deformation in passing through the rolls, and therefore "springs back" to a slightly greater thickness as soon as it is released from the pressure of the rolls. This, however, is a much smaller effect than that due to deflection of the rolls themselves. One important consequence of the elastic bending of the rolls is that the rolls themselves, where it is desired to roll flat sheets, cannot be used in the form of parallel cylinders; each roll must be given a certain small but appreciable thickening towards the middle, known as "camber." If the amount of this camber is not rightly adjusted to the work in hand, the resulting sheets are cockled instead of being flat—a result which arises if, through unequal pressure of the rolls, one region of the sheet receives a greater amount of pressure, and therefore of extension, than the rest. If the rolls are too much cambered, then the centre of the sheet receives the extra pressure, and the sheet as a whole appears "dished" or domed. On the contrary, if the rolls are too little cambered, *i.e.* too flat, the extra pressure comes upon the sides of the sheet, and there is a tendency for the edges to cockle or curve.

Rolling operations are sometimes of an elaborate kind, where the resulting product is to be a bar of complicated cross-section. A modern tramway rail is a good example of a section of that kind, and the design of the grooved rolls in which such a section is produced, starting from a rectangular or circular bar of solid section, offers many points of interest with which we cannot deal here. The governing principle in all such cases, however, must be that the amount of work, and therefore of extension, applied to various parts of the section must be equal, and that the cross-sectional areas of all parts of the various grooves must be adjusted to that end, due allowance being made for the fact that the linear velocity of the roll surface at the bottom of a deep groove is necessarily lower than that of the outer surface of the roll—a difference which is, of course, much more important with rolls of small diameter than in the case of larger rolls.

Metal is rolled both "hot" and "cold," but these terms are to some extent relative. Thus rolling aluminium at 400° C. is rightly to be regarded as "hot-rolling," but steel rolled at that temperature would have to be regarded as being "cold-rolled." As a rule, however, the latter term is applied only to operations in which the metal is not specifically heated before being introduced into the rolls. The distinction between "hot" and "cold" rolling is, however, much more than a nominal one, since the effect on the metal is widely different according as the rolling operation is carried on at a temperature high enough to allow of the rapid recrystallisation or annealing of the metal (hot-rolling), or the temperature is sufficiently low to prevent any spontaneous annealing. Thus lead would undergo the equivalent of "hot-rolling" at a temperature of 100° C., while steel is "cold-rolled" at any temperature below 500° C. The actual direct effect of the rolling process upon the metal is probably very similar whatever the temperature at which it is applied: the constituent crystals of the metal become flattened and elongated in the same sense as the piece of metal as a whole, and this change of shape occurs by the process of intra-crystalline slip which is described elsewhere (see article on "Metals, The Relations of Strain and Structure"). Where the temperature is below the annealing range of the metal, however, this deformation of the crystals, and the consequent very considerable hardening of the metal, persists, and the resulting product possesses much greater hardness and higher tensile strength, combined with much reduced ductility — all these being typical features of "cold-worked" or "work-hardened" metal. With each successive pass through the rolls this work-hardness increases, and after a certain amount of reduction has been applied the metal becomes too hard to permit of further cold-working; if the attempt is made to carry the process further the material begins to crack and break up. Before this stage is reached an intermediate annealing operation is usually applied to the material, after which further cold-rolling may be done. As a rule this intermediate annealing process is quite simple: the metal is pushed into a furnace heated to a suitable annealing temperature and allowed to remain there for a certain time. A curious phenomenon is, however, encountered in this connection, particularly where bars or slabs of considerable thickness have been cold-rolled. If the amount of deformation (reduction) which has been applied since the previous annealing has been large—not less than 50 per cent of the previous thickness—nothing special occurs. If, however, only light reduction has been applied, of the order of 20 or 30 per cent, when the bar or slab is pushed into the annealing furnace it is very apt to crack violently. This "fire-cracking" can be entirely prevented by a previous heat treatment at a much lower temperature. Thus in a bronze alloy which is ordinarily annealed at 700° to 750° C., a previous short period of heating to 350° C. entirely obviates fire-cracking. This action is readily understood, since the whole phenomenon arises from the existence, in the thick pieces of cold-rolled metal, of severe internal stresses arising from the fact that the outer layers have—under the relatively light passes — suffered more

extension than the inner ones. If such a piece is suddenly heated, the outer layers are weakened by the rise of temperature before the internal stresses have had time to release themselves by gradual deformation of the metal, and sudden fracture results. These internal stresses, however, can be almost entirely released by somewhat longer exposure to a lower temperature, which is not high enough to weaken the outer layers to the point of immediate fracture under the existing stresses. A more obscure phenomenon, however, is this, that "fire-cracking," at all events in nickel-zinc-copper alloys, can also be prevented by a process known as "springing," which usually consists in passing the cold-rolled bars through a machine which alternately bends them over rollers of moderate size—vigorous striking of the bars with a heavy wooden mallet, however, also serves the purpose. This mechanical treatment must, in some fashion, also bring about a release of internal stresses, but the manner in which this occurs is not understood.

In the operation of "hot-rolling," while the initial process of deformation of the constituent crystals of the metal is very similar to that which occurs in cold-rolling, an annealing or recrystallising process immediately follows the deformation. There is thus no "work-hardening" in the case of hot-rolled metal, and the operation can be continued without intermediate annealing or reheating until the metal has cooled too far and thus begins to enter the region where "cold-rolling" would occur. If the rolling process is stopped well before this stage is reached, then the hot-rolled product is quite soft, and the constituent crystals are not appreciably elongated in the direction of rolling. There are, none the less, indications in the micro-structure of material which has been hot-rolled, of the direction of rolling. Thus the two constituents of a duplex alloy, for example, tend to lie in lines along the direction of rolling, and this is particularly well seen in the case of non-metallic enclosures, such as those frequently met with in steel. There may also be banding running in the direction of rolling, arising from another cause, but the individual constituent crystals are none the less free from any direction of greatest length, *i.e.* they are approximately "equi-axed." If, on the other hand, the rolling operation is not stopped at so high a temperature, a certain—usually small—amount of "cold work" is put upon the material at a stage when it is already too cold to undergo spontaneous annealing, and the resulting material is both harder and less ductile than in the truly "hot-rolled" condition. This use of a relatively low finishing temperature is often employed in the production of rolled material which must pass a certain test for tensile strength while the degree of ductility insisted upon is not very stringent. It should, however, be borne in mind that the increase in tensile strength obtained by "cold work" is more apparent than real, particularly where the material is exposed to alternating or "fatigue" stresses. Extreme cold-rolling is, however, as a rule adopted only where a specially good surface finish is required on thin material.

The rolling process, which we have briefly considered above, serves for the production of metal in the form of bars or rods of various sizes and sections, and of sheets or strips. As a rule, however, it is not found convenient or satisfactory to carry the rolling process beyond certain limits, at all events where bars or rods are concerned. Rods of smaller diameter than about 0·5 inch are usually required in very considerable lengths, and these can only be produced by a rolling operation in special continuous rod mills, which have been particularly developed in America. In these mills the hot steel billet or thick, short bar emerges from the reheating furnace and enters a relatively slow-running pair of rolls in which its section is reduced and its length correspondingly increased. The bar as it leaves these first rolls immediately enters a second pair in which further reduction takes place, and so on, until rod or wire of the desired diameter is produced. It is, however, necessary that each of these successive pairs of rolls should run faster than the previous pair in order that they may deal, in the same time, with the very much greater length of rod. The final pair of rolls in such a mill, therefore, runs at an amazingly high speed, and the finished wire emerges at the speed of an express train. If, as may occasionally happen, anything occurs to interfere with the regular working of any of the rolls, or a rod end misses its proper point of entry, the whole of the building becomes rapidly entangled in a mass of writhing red-hot steel wire or rod; in spite of accidents of this kind, however, the continuous wire-mill has proved eminently successful.

§ (7) Wire-drawing.—For most purposes, however, rod or wire of smaller diameter than 0·5 inch is produced in an entirely different manner, by a series of operations known as "drawing." Here the thickness of the rod is reduced by forcibly pulling it through a hole in a steel plate or "die" which is distinctly smaller than the diameter of the rod. For this purpose the forward end of the rod is slightly swaged down or tapered so that the end may enter the die. The small piece which projects through the hole is then gripped in suitable pincers, and these are attached to a heavy moving chain which applies the necessary

force to draw the rod through the hole, thus reducing its sectional area and correspondingly increasing its length. A diagram of the actions which occur in this process of "cold-drawing" is shown in *Fig.* 4, which shows some resemblance to that illustrating the action of the rolling-mill (*Fig.* 3). But in the case of the die the metal is pulled forward by a tractive force applied outside the die, while the surfaces in contact with the metal are at rest and the metal slides over them under heavy frictional resistance. Rod- or wire-drawing is always carried out with cold metal, and the material becomes correspondingly work-hardened. After a certain amount of reduction has been applied the metal requires to be softened by annealing. If this is not done at the proper time the metal begins to break up, but the cracks first formed are frequently internal, and the metal is said to be "hollow drawn." This condition is diagrammatically represented, in section, in *Fig.* 5. The reason for this peculiar type of failure lies in the fact that, in drawing, the exterior layers of the rod or wire receive more work-hardening than the interior, being laterally compressed by the pressure of the die as well as elongated by the tractive forces. At a certain stage, therefore, the exterior layers are able to bear a tractive stress which fractures the less hardened internal layers.

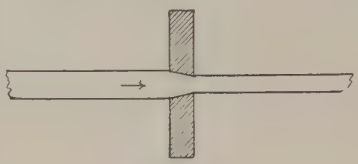

Fig. 4.

Fig. 5.

When the drawing process has been carried to a certain stage the product becomes wire rather than rod, and further drawing can then be carried out on the appliance known as the wire "block," in which the wire is pulled through the die by being coiled on a heavy iron block which is caused to rotate under power. Where fine wire is drawn, it is frequently passed through a whole series of dies and over suitable pulleys before it is finally coiled on the "block."

Fig. 6.

In addition to rod and wire, drawing operations are employed in the production of tubes. Tubes are sometimes made by the bending and welding of strip-metal of suitable width and length, the edges being joined by welding or brazing. Weldless or jointless tubes are, however, made by cold-drawing. Here the operation generally commences with a thick-walled hollow cylindrical or tubular casting, and the diameter and wall thickness are reduced together by drawing through suitable dies. It is, however, necessary to support the inner walls of the tube so as to prevent collapse, and also in order to secure a pressure upon the die sufficiently high to bring about the desired reduction in wall thickness. For this purpose tubes are generally drawn on or over a central rod of solid steel, known as a "mandril," which passes through the dies, inside the tube, without itself undergoing any change. Actually, the drawn tube is pressed very firmly on to this mandril, and special appliances are required for drawing the tube off the mandril. A diagram of the tube-drawing process thus briefly described is shown in *Fig.* 6.

§ (8) Extrusion. — In addition to the various forming processes which have been discussed very briefly above, another method is available whereby many metals may be readily and rapidly brought into certain useful shapes. This is the process known as "extrusion," in which the previously heated metal is placed in a heavy steel cylinder, and is then pressed or forced out through a suitably shaped aperture by the heavy pressure of a ram operated by hydraulic power. The presses used for this purpose are generally very heavy, pressures up to 10,000 tons being employed. There is, accordingly, some difficulty in finding dies, cylinders, and especially rams able to withstand such large pressures. The process is mainly used in the forming of brass rods or bars of various sections, although tubes can also be extruded, both with and without a mandril. By the choice of suitable die openings, it is possible to extrude bars having sections of complicated form which it would not be possible to produce in any other way, and even for the production of simpler sections the process offers advantages in regard to speed and simplicity of working. There are, however, a number of more or less serious difficulties connected with it. The heavily stressed rams of the extrusion presses are apt to fail by slight bending, while the dies and die-plates are liable to crack under the high bursting pressure. As regards the metal undergoing extrusion, it is found to flow much like a viscous liquid, and relatively slight defects in the billet or ingot are liable to be drawn out into long flaws which may

run down the entire length of a bar. For this reason extruded bars are liable to show a certain laminated structure, and, generally, their mechanical properties are not so satisfactory as those of properly rolled metal of the same composition. On the other hand, it is perfectly possible to extrude alloys which it is extremely difficult, if not impossible, to roll, and if first extruded into relatively thick bars such alloys can then be successfully hot-rolled into thinner bars or strip.

§ (9) Secondary Processes.—The methods for the mechanical treatment of metals which have so far been considered may be regarded as the primary shaping or forming operations, commencing with the product of the foundry—the cast ingot or slab—and converting it either into the final product or into an intermediate product ready for further forming or shaping processes, which—starting with previously wrought material—may be regarded as secondary operations. Among these secondary operations may be mentioned such processes as drop-forging or stamping, in which metal in the form of rolled bars or sheets is pressed into the desired final shape, usually while hot, although cold-stamping can be done with the softer metals in relatively thin sections. Here forming-blocks or dies are used, and these require considerable care in design to allow of the ready flow of the right amount of metal into the various parts. The value of the finished product often depends upon the manner in which the material has been caused to flow during drop-forging. Such forming operations as the stamping of sheet-metal are frequently accompanied by a combination of pressing and drawing which, in its mode of action, has some resemblance to the tube-drawing operations mentioned above. The production of an ordinary brass cartridge-case such as that used with military small-arms ammunition is a striking example of the very large changes of shape which can be brought about by such operations.

The products of all cold-forming operations, unless they are finally annealed, are left not only with the metal in a largely work-hardened condition, but also in a condition of more or less severe internal stress. If this state of stress is unduly severe, and if the metal itself is in a favourable structural condition, the object may, in the course of a longer or shorter time, undergo apparently spontaneous fracture. This phenomenon is well known under the misleading name of "season cracking" in brass and other alloys. Fractures of this kind are, it is well known, considerably accelerated by any corrosive action to which the object may be exposed. A very rapid action of this kind may be brought about by exposing a cold-worked brass object to contact with a solution of a mercury salt, such as mercuric chloride or mercurous nitrate. The metallic mercury which is liberated in such conditions rapidly penetrates the strained brass, and fracture occurs in a few seconds or minutes. Fracture in all these cases takes place in a typical manner by the pulling apart of the constituent crystals of the metal, while—if the same metal is broken in a testing machine in tension or bending—the normal fracture takes a path mainly across the crystals themselves. This subject is referred to at greater length elsewhere (see article on "Metals, The Relations of Strain and Structure—Amorphous Metal").

§ (10) Cutting.—The final mechanical treatment to which many metal objects are exposed is that of cutting by means of some form of tool, generally in a machine tool such as a lathe or a milling machine. It is, however, outside the scope of the present article to enter at all fully into the question of the cutting or machining of metals and the action of cutting tools generally. From the point of view of the treatment of the metal which is being cut, it need only be said that the mechanical effects of machining are surprisingly small. A small degree of surface hardening (work-hardening) undoubtedly occurs; but even where heavy cuts at high speeds have been taken by powerful modern high-speed tools, the depth of the cut metal which is appreciably affected is very small. Where specimens have to be prepared for microscopic examination, this distorting effect of cutting-tool action is of considerable importance, but from the mechanical point of view an appreciable effect can only be met in very thin sections. There are, however, a few exceptions which are of some interest. They arise mainly in connection with the cutting of hardened steel by means of powerful carborundum or emery grinding-wheels. These wheels are liable to generate very great heat at their point of action, and may even raise the steel locally to a red heat. If this should occur during the grinding of a piece of hardened steel, the steel will be seriously softened wherever such a temperature has been reached, while the volume changes which accompany the tempering and softening of steel are liable to lead to serious cracking, commencing from the "hot" or "soft" spots.

From the point of view of the cutting operation itself, the physical properties of the metal being cut are of considerable importance. The hardest metals, particularly the hardened steels, are of course too hard to be cut by a steel tool, and the use of grinding-wheels must be relied upon. Modern developments have, however, rendered such grinding operations much easier and cheaper than formerly. At the opposite extreme as regards difficulty of machining are the very soft

metals, such as copper and aluminium. Here the very great ductility of the metal hinders the action of the tool. It must be borne in mind that a cutting-tool of any kind, in reality, produces a series—more or less continuous—of fractures in the metal which is being cut. These may be either shear fractures or fractures under compression, but in either case, if the metal is extremely ductile, it will become much more difficult to bring about fracture; the edge of the tool will be liable to become buried in the metal, whose ductility enables it to spread the intense crushing pressure of the tool edge over a wedge-shaped area slightly surrounding the cutting edge itself. It is for this reason that very soft metals are very difficult to machine. As soon as the ductility of the pure metal is slightly reduced by the presence of hardening elements, the cutting properties improve in a remarkable manner. We may compare, from this point of view, brass with copper and some of the alloys of aluminium with zinc and copper with pure aluminium. Certain of these latter alloys have now earned the reputation of being the best materials for accurate and delicate machining which have yet been obtained.

§ (11) Annealing and Heat Treatment.—The various forms of treatment which have been considered so far are all related to the process of bringing a mass of metal into some desired shape, and even where the operations produce an important effect on the internal structure and physical properties of the material, they are always connected with changes of external shape. There is, however, a whole group of processes of thermal treatment which are not associated with any operation involving a change of shape of the metal, and whose action is confined to an effect—which may be very powerful and profound—upon the internal structure of the material. These operations include annealing, normalising, quenching, and tempering, and if our conception of "thermal treatment" is widened to include operations which involve a change in the chemical composition of the metal treated, such processes as case-hardening, "malleablising," and "Sherardising" must also be included.

The operations known as annealing are applied for the purpose of rendering metal softer and more ductile, either by removal of hardness arising from cold work or from quenching, or by the removal of internal stresses arising from rapid cooling or other causes. For the latter purpose it has been found that very moderate amounts of heating are adequate, although the mechanism by which internal stresses can be relieved at temperatures far below those at which crystalline rearrangement takes place is by no means readily understood, although some tentative explanations have been suggested (see article on "Metals, The Relations of Strain and Structure — Amorphous Metal"). Annealing in the more usual sense of the word as used by metallurgists, however, implies heating to a temperature high enough to bring about or, at all events, to permit at least gradual recrystallisation. The removal of hardness caused by cold work, and that of hardness due to quenching in certain metals, must be considered separately.

Severely cold-worked metal is known to exist in a metastable condition, from which it tends to revert to the soft state. According to the view first put forward by Beilby, the hardness of cold-worked metal is due to the partial destruction of the crystalline structure of the metal and the formation of numerous layers of a hard, amorphous phase (see "Metals, The Relations of Strain and Structure," § (3)). On this view, the softening of strain-hardened metal by annealing is simply due to the fact that the elevated temperature permits the amorphous material to revert to the soft, crystalline state. Although the earliest stages of this process cannot be followed with the microscope, because complete mechanical softening occurs in many metals before there are any marked signs of crystalline rearrangement, the subsequent behaviour of metal during annealing strongly confirms the general view. On heating cold-worked metal, a set of entirely new crystals are generally formed, and these tend to increase in size and to decrease in number on prolonged heating or with an increase of temperature. This process, however, does not continue indefinitely in ordinary circumstances, as a permanent or quasi-permanent condition of crystal size is reached after a certain length of annealing. Generally speaking, an increase of annealing temperature induces an increasing coarseness of crystalline structure, with corresponding changes of mechanical properties which, for most purposes, are to be regarded as deterioration, *i.e.* some loss of strength and very considerable lowering of the elastic limit.

The actual temperature at which annealing takes place varies widely in different metals. As has been indicated above, lead and tin undergo spontaneous annealing and recrystallisation at room temperature, and undergo rapid annealing at 100° C. In very pure gold, annealing has been found to occur, after severe cold-working, at temperatures as low as 150° C.[1] Aluminium and its alloys require temperatures of about 200° to 250° C. to undergo softening. Brass undergoes fairly rapid softening at 400° C. In cold-worked iron or steel, on the other hand, the first signs of softening and recrystallisation do not occur

[1] Rose, "On the Annealing of Gold," *Inst. of Metals J.*, 1913, ii.

until a temperature somewhat above 500° C. is applied.[1]

The annealing of metal which, like hardened steel, has been hardened by quenching from a high temperature differs materially in its nature from the softening of strain-hardened materials. In the case of steel, which is fully treated elsewhere (see articles on "Iron-carbon Alloys" and on "Steels, Special"), hardness is conferred by quenching from some temperature above a certain critical point or range. The result of such quenching or rapid cooling is to retain the steel in a condition—as regards internal constitution—approximating to that in which it existed at the high temperature, and thus to suppress, more or less completely, the transformation or phase change which would normally occur, at moderate rates of cooling, on passing through the critical point in question. The quenched material is thus in a highly metastable condition, and tends to revert to the more stable state as soon as rise of temperature allows of greater freedom of atomic arrangement. Accordingly, steel which has been fully hardened by cooling it very rapidly from a temperature above the critical point is gradually softened or "tempered" when it is gradually heated. This gradual softening or tempering increases in amount as the temperature is raised, until—when the reheating or tempering temperature reaches or closely approaches the critical point—the softening is complete, and the steel may be regarded as not merely "tempered" but as "annealed." Originally applied mainly to steel hardened for use in cutting-tools and requiring varying degrees of tempering when intended for various uses, the processes of hardening by quenching and subsequent tempering have now come to be very widely used, particularly in the heat treatment of special or alloy steels (see article on "Steels, Special"), and even ordinary carbon steels are now frequently refined by being subjected to such a process of hardening and tempering. From many points of view, this type of treatment may be regarded as a means of imparting to the steel a particularly refined and homogeneous structure; where this is not quite so important as to justify the relatively elaborate process in question, an approximation to a similarly refined internal structure may be obtained by a single operation which is now usually known as "normalising." In quenching, followed by tempering, the severe effects of very rapid cooling, produced by dipping in water or oil, are to some extent undone by subsequent reheating; if, however, the original rate of cooling is not quite so rapid, a somewhat similar ultimate effect can be produced direct, *i.e.* without subsequent reheating. This is done in the "normalising" process by heating the piece of steel to a temperature above the critical range and then allowing it to cool rapidly in the air. This process is mainly applicable to carbon steels. Certain alloy steels become more or less fully hardened by such treatment, and then require subsequent tempering.

The operations involved in the heat treatment of steel, as very briefly outlined above, are in modern practice applied not merely to small objects such as tools, but also to the largest products of metallurgical industry, such as guns and armour plates. The quenching of large objects is a matter of considerable difficulty, owing to the importance of securing a uniform temperature in the object at the moment of quenching, and also a uniform exposure to the cooling agent. Thus the largest gun-tubes, measuring up to 70 feet in length, are heated prior to quenching in tall vertical furnaces, and are then dropped vertically into a deep shaft-like tank containing oil (cotton-seed oil or whale oil is generally employed). Armour plate is more usually chilled by exposure to a fine spray of water. The choice of the quenching liquid is of considerable importance. Water produces the most vigorous cooling effects, but is correspondingly liable to cause cracking, owing to the volume changes which occur during hardening. Oil gives much lower rates of cooling, but is correspondingly safer as regards cracking, while the rate of cooling is still fast enough to secure a degree of hardness adequate for many purposes. It has been found that the quenching power of a liquid is only slightly affected by its actual thermal conductivity, but depends a great deal on the specific heat of the liquid, while its boiling-point, latent heat of vaporisation, and viscosity also affect the result. Mercury, in spite of its high thermal conductivity, affords less vigorous quenching than certain kinds of oil.

The operations of quenching and annealing are frequently used in the laboratory in connection with the investigation of the constitution of alloy systems. In order to secure specimens of an alloy which has attained, or nearly attained, an equilibrium condition at some selected temperature, it is generally necessary to maintain the specimen at that temperature for many hours. A still better method consists in first cooling the specimen exceedingly slowly down to the selected temperature from a higher one, and then maintaining it there for a long time. Special thermostats, working on the principle of the gas thermometer, have been devised

[1] Goerens, "Influence of Cold-working and Annealing on the Properties of Iron and Steel," *Iron and Steel Inst. J.*, Carnegie Scholarship Memoirs, 1911.

by means of which both very gradual cooling and the maintenance of any desired temperature up to 1000° C., with a variation of not more than ±1° C., can be secured.[1] It is further necessary, in many cases, to observe specimens of metal which have been quenched or chilled from a definite annealing temperature, the object aimed at being to retain, as nearly as possible, the exact internal structure which was present in the specimen at the moment of sudden cooling. A special quenching apparatus has been devised for this purpose, in which the small specimen of metal lies in a tube of vitreous silica passing through a small electric resistance furnace. The silica tube is exhausted, one end being connected with an air-pump, while the other is closed with a large-bore glass tap which shuts the tube off from a vessel containing the quenching fluid, such as cold water. When the specimen is to be quenched, the electric current is switched off and at the same time the large tap is opened. The water, under the pressure of the atmosphere, sweeps into and through the silica tube and rapidly chills the small piece of metal.[2] This quenching operation is often used for the purpose of ascertaining the precise temperature at which the first signs of incipient fusion become perceptible in an alloy. In a quenched specimen the presence of even minute specks which were actually liquid at the moment of quenching is readily detected, so that the examination of a series of specimens quenched at successively higher temperatures makes it possible to determine with considerable accuracy the "solidus" or temperature of complete solidification of the alloy in question.

§ (12) Case-hardening.—Of processes which combine chemical with thermal action, that known as case-hardening may be taken as typical. The purpose of this process is to provide a piece of soft mild steel with a thin hard outer covering or case for the purpose of enabling it better to resist wear. This object is attained by causing the outer layers of the soft steel to take up an increased amount of carbon by absorption from a suitable environment, and following this by a quenching process which hardens this outer layer of high-carbon steel while it does not harden the core of original soft steel. The operation is carried out by embedding the piece of steel in a carburising medium, which generally consists of carbon in the form of charcoal mixed with some other substance, such as barium carbonate, and enclosing the whole in as nearly an air-tight manner as possible in cast-iron boxes. The whole is then heated, generally to a temperature of about 900° C., for a number of hours, during which carbon passes into the outer layers of the steel. Subsequently, the carburised steel is subjected to a double quenching, and sometimes to a final tempering process. An extensive literature has been created in connection with this process.

The converse to the process of case-hardening is that whereby the usually hard and brittle castings made of "white" cast iron are rendered soft and "malleable"—hence the process is sometimes known by the inelegant name of "malleablising." Here the casting is packed in iron oxide and also exposed to heat for a considerable number of hours. The result is a partial removal of carbon from the casting, but there is also an extensive and beneficial rearrangement of the internal constituents of the cast iron, particularly a deposition of some of the carbon in the form of a special variety of finely divided graphite. Together, these changes render the casting soft and to some extent ductile.[3]

Somewhat analogous to case-hardening is a process which is applied to non-ferrous metals as well as to iron and steel, known as "Sherardising." Here the object is not to furnish the metal with a hard coating capable of resisting wear, but with a coating capable of resisting corrosion. The metal applied is zinc, and the process consists in embedding the article to be treated in zinc dust in closed boxes and heating these to a moderate temperature (600° C.) for a few hours. The article becomes coated with an adherent layer of zinc, and this metal also penetrates into the article to a slight depth. A somewhat similar treatment in which the coating produced consists of a mixture of aluminium and aluminium oxide is known as "calorising," and is employed to protect iron or steel against scaling when exposed to high temperatures. These latter processes, however, can scarcely be regarded as constituting thermal treatment of the metals which are coated, so that they fall somewhat outside the scope of the present article.

W. R.

[1] Haughton and Hanson, "A Thermostat for Moderate and High Temperatures," *Inst. of Metals J.*, 1915, ii.; "Further Notes on a High Temperature Thermostat," *ibid.*, 1917, ii.

[2] Rosenhain, "The Metallurgical and Chemical Laboratories at the National Physical Laboratory," *Iron and Steel Inst. J.*, 1908, i.

[3] Hatfield, W. H., *Cast Iron in the Light of Recent Research* (C. Griffin & Co., Ltd., London).

METALS, THE THERMAL STUDY OF

(The figures in brackets refer to the References at the end.)

The thermal study of metals has proved one of the most fruitful methods of exploring the internal equilibria of alloys and the transformations which metals undergo. Fundamentally, the method consists in determining the temperatures at which metals give out or absorb heat while being heated or

cooled; but when carefully applied with the aid of suitable apparatus the method also furnishes at all events an approximate estimate of the amount of heat which is evolved or absorbed during any given change. While thus fully recognising the fundamental importance of the method as a means of studying alloy systems, it should be borne in mind that it is not capable, by itself, of furnishing complete insight into thermal equilibria, and that the attempts which have been made by some workers to rely entirely upon its indications in establishing equilibrium or constitutional diagrams have led to unreliable results. The best use of the method lies in furnishing an almost unfailing guide to the study of the micro-structure of any alloy system, and in affording the necessary data on which annealing and quenching experiments can be based.

§ (1) Thermal Curves.—The study of thermal changes in metals and alloys during heating and cooling is usually conducted by the preparation of heating and cooling curves, or—as they are comprehensively called—thermal curves. These may be determined experimentally in a variety of ways, and are capable of graphic representation by various methods, the more important of which are described below. Essentially, however, the experimental method always includes the observation of the temperature changes which occur in a specimen of metal while heat is supplied to it or abstracted from it in the most regular manner which can be practically realised. So long as the sample under observation undergoes no changes which absorb or liberate heat, its temperature changes correspond merely to the rate of application or withdrawal of heat; so soon, however, as the metal undergoes a change involving heat absorption or evolution, its temperature no longer follows the same regular course, and observations of its temperature indicate a more or less marked irregularity—some departure from the rate of heating or cooling which had previously been in progress. Any graphical representation of such observations indicates at such points a departure from regularity which is generally termed a "critical" point or range.

§ (2) Furnaces.—The thermal study of metals requires first the provision of means for heating and cooling the specimens under observation in a sufficiently regular and uniform manner; means for measuring and recording the temperature of the specimen are then required, and finally graphic representation is given to the observed data in various ways whose physical interpretation is of importance. The subject will, accordingly, be treated in regard to these various aspects in approximately the order stated.

(i.) *Natural Cooling.*—The simplest and most obvious method of heating and cooling a small specimen of metal is to place it in a small furnace and allow it first to become heated together with the furnace, by the operation of a flame or an electric current, and then to allow the specimen to cool naturally with the furnace after the supply of heat has been cut off. Where observations during cooling only are required, some degree of success can be attained by this simple method, since most ordinary laboratory furnaces, whether gas-heated or electric, cool sufficiently steadily for the purpose. In regard to observations during heating, however, the position is very different. Gas-heated furnaces very rarely show a sufficiently steady rate of heating, while with most electric furnaces it is not possible to carry out heating from the ordinary temperature up to, say, 1000° C. without several adjustments of the heating current. Such adjustments, however, introduce abrupt changes in the rate of heating, and these interfere with thermal observations. Consequently, so long as investigators confined themselves to these simple furnaces, the application of the thermal method remained almost entirely restricted to cooling curves, a limitation which materially lessened the value of the thermal method as a whole.

There is a further serious disadvantage which attaches even to cooling-curves taken by simple "natural" cooling. In these circumstances, at the beginning of a series of observations for a cooling-curve, the rate of cooling is rapid, since the piece of metal and the furnace surrounding it are both very hot and undergo rapid "natural" cooling. As the actual temperature falls, the rate of cooling decreases very considerably, and at relatively low temperatures becomes very slow indeed. Now the maximum rate of cooling cannot for most purposes be allowed to exceed a fall of 9° C. per minute, and to restrict natural cooling to this rate at a temperature above 1000° C. requires either a very large and heavy furnace or very good thermal lagging. The consequence is that when the temperature falls below 400° C. the rate of cooling of a heavy well-lagged furnace becomes excessively slow. This is very undesirable, for a number of reasons. In the first place, instead of the ideal straight-line curve which it is desired to approach in the case of a body free from thermal changes, a markedly curved graph is obtained, with the result that the base-line to which any thermal irregularity must be referred varies widely according to the part of the temperature range where the irregularity occurs. This makes it very difficult to form even the roughest estimate of the real magnitude of various thermal changes which may come under observation.

Further, there is a lower limit to the rate of cooling which it is permissible to use when looking for evidences of thermal transformations. With unduly slow cooling, the temperature effects of anything but a large heat-evolution become almost entirely smoothed out, and it is quite obvious, from an inspection of certain of the constitutional diagrams put forward by some of the earlier workers in this field that important thermal changes have been entirely overlooked from this cause. The very slow cooling at relatively low temperatures has the further serious disadvantage that it adds seriously to the time occupied by the observations for a cooling-curve. Various attempts have been made to overcome these difficulties. Thus the cooling-curve might be taken in two or more series of observations, made in different furnaces, each covering a range in which its rate of cooling was satisfactory. Even if these various ranges are made to overlap considerably, this is not a safe proceeding, because, in certain alloys at all events, the nature of the lower critical points depends to a large extent upon the actual maximum temperature from which that particular cooling process has been begun, and upon the rate at which certain of the upper critical ranges have been traversed.

(ii.) *Electric Furnaces.*—In view of these considerations, efforts have been made by several workers to devise apparatus in which specimens of metal under thermal observation could be heated and cooled not only at a steady but at a uniform rate throughout the entire range of temperature required for such observations. Broadly, two possibilities present themselves. The first, and perhaps the most obvious, is to construct an electrically-heated furnace whose temperature will respond very rapidly to any change in the heating current. With such a furnace, if means are provided for steadily and gradually altering the current in-put according to some predetermined law, it is possible to obtain uniformly rising or falling temperatures. A furnace, however, which rapidly follows variations in the heating current must necessarily be one having very small thermal capacity as compared with its cooling surface; it will therefore be very inefficient from the thermal point of view. In other words, a furnace that will cool sufficiently fast, even with the heating current entirely cut off, say at 400° C., must necessarily require a very high current in-put at 1000° C. While this may not be a serious matter from the point of view of the cost of electric energy for such a purpose, it entails at least one very serious disadvantage. The less efficient any electric resistance furnace is, from the thermal point of view, the higher is the actual temperature to which the heating resistance itself must be raised in order to attain a given temperature in the furnace. This overheating of the furnace winding is the most fruitful cause of rapid deterioration and "burning out" of such furnaces. In view of the serious cost in time and materials which frequent re-winding of furnaces entails, this constitutes an important objection to the use of the method just outlined.

There is also the further objection that the regular variation of the heating current according to a pre-determined law, which is required in order to secure uniformity in the rates of heating and cooling over a wide range of temperature, demands a somewhat complicated electrical installation. In spite of these difficulties and objections, this method has been adopted and employed with very remarkable success by Burgess and Crowe (1) at the Bureau of Standards in Washington. Their published curves, particularly those relating to pure iron, show how closely their apparatus approaches the ideal condition of uniform rates of heating and cooling.

The other possibility is to abandon entirely the principle of allowing furnace and specimen of metal to change their temperatures together and to substitute an apparatus in which the temperature of the specimen is changed at the desired rate by moving it from a cool to a hotter place or *vice versa* in a suitably-designed furnace. For this purpose it is necessary to construct a furnace in which there is a suitable steady and uniform temperature gradient and to employ some means of moving the specimen steadily and gradually in the direction of this gradient. This method has been adopted very successfully at the National Physical Laboratory (2), and it has been found possible to employ it without the introduction of any elaborate appliances.

(iii.) *Gradient Furnaces.*—The "gradient furnace" used for this purpose consists of a vertical tube heated electrically at one end and kept cold at the other. It has been found that in this way a satisfactory temperature gradient is obtained, a tube 36 inches long being uniformly wound for a length of only 8 inches at the upper end. It is not suggested that the actual temperature gradient in the furnace itself is strictly uniform. If a series of thermo-couples were inserted at a number of points in the length of such a furnace and their indications were plotted against their position in the furnace, it is not anticipated that a straight line graph would be obtained. The gradient is, however, such that a piece of metal which is moved up the centre of the tube at a constant speed rises in temperature at a constant rate so long as it undergoes no internal transformations. This condition is easily verified by taking a "blank" curve with a piece of platinum which, up to 1000° C. at all events, undergoes no thermal changes.

The heating of such a piece of metal, however, is due, in part at all events, to direct radiation from the hot end of the furnace tube as well as to more direct heating from the sides of the tube in the immediate neighbourhood of the specimen, so that a strictly uniform temperature gradient in the furnace itself would probably not lead to a uniform rate of heating. None the less it is found preferable to make the tubes of these furnaces of materials having the highest available thermal conductivity, since this is found to lengthen the useful region of the furnace very appreciably. For temperatures up to 700° C. iron tubes are found successful. For higher temperatures more refractory tubes such as fire-clay or "alundum" have been used, but more recently a special heat-resisting alloy known as "Reactol" has become available, and this is found satisfactory up to temperatures of 1000° C.

In order to avoid convection currents, which would interfere seriously with the working of such a "gradient" furnace, it is found necessary to close the lower end of the vertical furnace tube in an air-tight manner, the hot end of the furnace being always placed at the top. In the more usual type of furnace, the metal specimen is suspended through the open top, which is fitted with stoppers that permit the necessary rods, tubes, or wires to pass into the furnace. Where the metal can be exposed to contact with air during the thermal observations, it is placed in a suitable receptacle, which is suspended by means of nichrome wires passing down through a tube of vitreous silica. Where, however, a controlled atmosphere or a vacuum is desirable, the specimen lies at the lower end of a long tube of vitreous silica. The lower end of this tube is sealed, while the upper end, which always remains well outside the furnace, is closed with a rubber stopper through which pass the wires of the thermo-couple and a glass tube connected with a stop-cock. This entire tube, with the specimen and thermo-couple wires in place, can be taken to a pump, evacuated, and then taken to the furnace, or, alternatively, the pump can be kept connected to the tube through a flexible connection, and exhaustion can be continued while the thermal observations are in progress. A tube of vitreous silica for this purpose may conveniently measure about 1 inch in internal diameter and have a length of 40 inches. For use with such a tube, however, the furnace tube itself should have a diameter of not less than $3\frac{1}{2}$ inches. If the moving tube or even the specimen in its bare receptacle is too nearly a fit in the furnace tube, the thermal conditions are unfavourably affected and undesirable complications are introduced.

In a more recent modification of this type of "gradient" furnace the arrangement for carrying the specimen of metal into and out of the hot region of the furnace has been inverted; the furnace is permanently closed air-tight at the top and the specimen, with its attached thermo-couple, is pushed up the tube from below by means of a rigid rod, either of metal (steel) or—for higher temperatures—of carborundum or other refractory material. This requires rather more elaborate mechanical arrangements, and very careful support for the thermo-couple wires is needed in order to avoid all risk of their being either ruptured by their own weight or pulled even slightly out of position in the specimen of metal. In other respects, however, this modification has the advantage that only the extreme end of the thermo-couple, situated in the specimen itself, is ever exposed to the maximum temperature, the rest of the couple wires being always cooler than the specimen. In the ordinary (opposite) arrangement, the couple wires pass through a region of the furnace at the top which is always hotter than the maximum temperature reached by the specimen, and this is a slight disadvantage in all cases. It becomes serious, however, if temperatures approaching the limits of usefulness of platinum-platinrhodium thermo-couples are to be observed, and it is for purposes of that kind that the inverted arrangement has been primarily adopted (3).

The method of moving the specimen up and down in the gradient furnace will depend upon the appliances available. Simple mechanical hoisting and lowering by the winding up of a cord or thin wire on a drum driven by gearing from a small electric motor has been used with success. Where the temperature measurements are made with highly sensitive apparatus, however, and it is desired to push accuracy to the greatest possible extent, a means of raising and lowering which gives a steadier motion is desirable. Wherever gearing is used, some backlash is inevitable, while an electric motor, even when driven from a storage battery, does not maintain a perfectly constant speed unless very carefully governed. For work entailing the highest accuracy, therefore, a simple gravity drive is preferable, and the rate of motion is then best controlled by the flow of a liquid, such as oil or water, through a small orifice. As it is very desirable that successive heatings and coolings in a series of determinations should be carried out at the same rate, the orifice used for regulating the flow should not be an adjustable one, but a series of definite orifices should be available, so that the same one may be used whenever the same rate of rise or fall is desired. Even then attention must be paid to the temperature of the liquid (oil or

water) since slight changes of temperature are liable to bring about relatively large changes of viscosity in the liquid.

§ (3) The Specimen.—The choice of the size and shape of the specimens of metal to be used for thermal examination is to some extent dependent upon the mode of heating and cooling which is to be adopted. As regards the mass to be used, it is evident that the total amount of heat which is absorbed or evolved by a given change in the metal will vary directly with the mass of metal which is present. On the other hand, the larger piece of metal inevitably entails the consequence that some parts of the specimen must be at a greater distance from the thermo-couple, which is, consequently, not so quickly affected by thermal changes which occur in the more remote parts of the specimen. Further, since the specimens of metal are always in process of either cooling or heating, a temperature gradient must exist in them, and this gradient must be the same for the same rate of change of temperature of a specimen of the same material, whatever its dimensions or in whatever manner it is being heated or cooled. It follows that in a larger piece of metal the maximum temperature difference between the hottest and the coldest portion must, for the same rate of cooling, be proportionately greater. But temperature differences between various parts of a specimen are a serious disadvantage, since it follows that in cooling, for example, the coldest portions of the specimen will reach a critical temperature, where a heat evolution occurs, a little before the hottest part of the specimen—which is generally near the centre where the thermo-couple is placed—has reached that same critical temperature. The heat-evolution occurring in the colder parts of the specimen, however, very soon begins to affect the thermo-couple by reducing the rate at which heat flows outward from the hottest parts. The thermo-couple will therefore begin to indicate a departure from normal steady cooling slightly before it has itself reached the temperature at which the beginning of the transformation really occurs. The maximum difference of temperature between the thermo-couple and the coldest parts of the specimen must therefore be kept very small if really sharp indications of the beginnings of critical changes are to be obtained. This consideration would suggest the use of small specimens, but where "natural" cooling is adopted there is the very strong countervailing consideration that with small specimens the rate of "natural" cooling is apt to be unduly fast, or, if this is controlled by the gradual cooling of a large furnace, then the heat evolutions due to the specimen will be merely small effects superposed on what is really the cooling-curve of the furnace. In the case of the gradient furnace, however, the considerations are somewhat different, since there the maximum temperature differences depend to some extent upon the shape of the specimen as well as on its mass.

For "natural" cooling, which takes place—approximately at all events—equally in all directions, it is obvious that the best shape of the specimen would be spherical; for a given mass, and a given temperature gradient, the spherical shape gives the minimum temperature difference between centre and outside of the specimen. In the gradient furnace, however, heating or cooling does not take place even approximately to an equal extent in all directions. In fact, in a specimen which is slowly moved along a tube heated at one end and cold at the other, while lateral heat losses are minimised by good thermal lagging, the isothermals would approximate to a series of planes at right angles to the axis of the tube. In such a case the upper surface would always be the hottest and the lower surface the coldest part of the specimen. In order, therefore, to diminish the differences of temperature which inevitably occur, it becomes desirable to concentrate the specimen into a shape approximating to that of a flat disc lying at right angles to the axis of the tube. In practice, a convenient shape for specimens which are not to be melted while under thermal study is that of a flat truncated double cone, as shown in diagrammatic section in *Fig.* 1. In

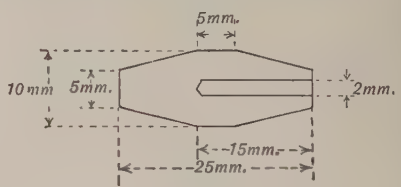

Fig. 1.

the case of alloys in which the thermal curves are to be taken so as to include the melting-point, the nearest approach to the ideal shape is obtained by using them in the form of a flat disc of metal lying in a shallow, flat-bottomed crucible, such as that shown in diagrammatic section in *Fig.* 2. In both cases the thickness of metal available in a vertical direction becomes too small to allow of the insertion of a thermo-couple with any satisfactory "depth of immersion." The plan has therefore been adopted of inserting the thermo-couple horizontally, in the central plane of the specimen. In the double-coned specimen this is easily arranged by drilling a horizontal, radial hole in the piece of metal, and inserting the thermo-couple directly into this in such a manner that the actual

junction lies close to the geometrical centre of the specimen. Where the specimen is to be contained in the shallow crucible, however, it becomes necessary to provide the crucible with a small lateral tube into which the couple can be pushed horizontally, again so as to lie close to the centre of the mass of metal.

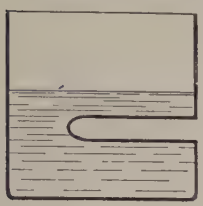

FIG. 2.

While it is, perhaps, a little more troublesome to insert the thermo-couple in this position, an important additional advantage is gained thereby. The entire couple, so far as it is within the specimen, lies in an approximately isothermal plane, and the wire as it leaves the specimen emerges into surroundings still at the same temperature. Disturbance of the indications of the couple by conduction of heat along its wires is therefore eliminated in a particularly satisfactory manner.

The question whether the various conditions outlined above have been satisfied to an adequate extent in any given experimental arrangement can be readily tested by comparing the heating and cooling curves obtained for a pure metal or for a pure binary eutectic alloy, both of which show single, sharply-defined melting- and freezing-points. If the shapes of the curves are similar and the temperatures of melting and freezing are found to coincide to the desired degree of accuracy, it may safely be concluded that the entire arrangement is satisfactory. It may be mentioned, however, that such critical points as those of steel cannot be used for making such a test, since they do not generally occur at the same temperature on heating as on cooling.

§ (4) TEMPERATURE MEASUREMENTS.—We pass, next, to a consideration of the methods by which the temperature and the temperature changes of the specimen of metal may be observed and recorded. Since the use of thermo-couples is now almost universal for this purpose, attention will be confined to them. The thermo-couples most widely used are those of which one element is pure platinum while the other is most frequently a wire of platin-rhodium containing 10 per cent of rhodium. Platin-iridium is sometimes used and has the undoubted advantage of affording a higher thermal E.M.F.; the tendency of iridium to volatilise, however, renders these couples somewhat less stable and therefore less reliable for this purpose. For temperatures below 700° C. it is possible to use certain base-metal couples, such as iron-constantan, which have the very important advantage of avoiding the excessive cost of platinum and its alloys and at the same time affording more than three times the thermal E.M.F. of the platinum couples. Special care is, however, required in regard to the frequent re-calibration of base-metal couples, and also in calibrating each new couple, on account of the fact that these alloys are not obtainable with the same accurate reproduction of composition and—consequently—of thermo-electric properties which has been achieved in platinum alloys. For very high temperatures, and where work can be carried out in a high vacuum, the use of couples consisting of tungsten and molybdenum wires has recently been suggested. Such couples, however, suffer from the serious disadvantage that the thermo-electric power passes through zero value and changes in sign at a temperature near 1300° C., so that the couple is entirely useless in that region. At higher temperatures it can be used, provided it is completely protected from the action of oxygen, but its thermal E.M.F. is very low. The use of wires of some of the highly refractory metals, however, offers such valuable possibilities that it may be hoped that other couples may be found which are free from some of the disadvantages named, although the prevention of oxidation must always remain a serious experimental limitation.

In all cases, it is found preferable that the actual junction of the two wires constituting the couple should be made by autogenous fusion. Generally this can be readily accomplished by fusion in the blowpipe, with the aid of compressed oxygen. Direct welding by means of a small electric arc, or even by striking a spark from suitably arranged condensers, between the wires to be joined, has also been successfully employed. Couples made by merely twisting wires together are not reliable, even in the case of the platinum metals, while the use of solders is to be avoided wherever possible.

The cold junctions of the thermo-couple are best kept at 0° C. by immersion in pounded clean ice. If such ice is kept in one of the small vacuum flasks which are now readily purchased, a single filling of a few ounces is sufficient for a whole day's work. Where the gradient furnaces are used, such a small vacuum flask containing the cold junctions is easily raised and lowered with the tubes and wires carrying the specimen itself, so that there need be no relative motion between the two ends of the thermo-couple. The cold junctions are connected to the electrical measuring apparatus by ordinary leads; only where extreme accuracy is aimed at do these require special attention. Then, however, possible minute electrical leakages from high-tension electric currents used for heating the furnaces or driving motors, etc., must be carefully guarded against. Another possible source

of error may arise from thermo-electric effects due to connections between leads and binding-screws of different metal, particularly where connections pass through a switchboard or similar appliance. For the best work it is probably worth while to use a single unbroken copper lead direct from the cold junction to the terminals of the measuring instrument.

(i.) *Direct Reading Instruments.* — The methods which have been employed for measuring the thermal E.M.F., and, thereby, the temperature of the specimen, vary very widely, ranging from the simple reading of a millivoltmeter having a pointer and scale a few centimetres long, to the use of elaborate forms of potentiometer in conjunction with special types of recording chronographs. The usual procedure is to allow the pointer of the millivoltmeter or the spot of light reflected from the mirror of a galvanometer to pass over a scale, and to note or record the times at which it passes certain points on the scale which correspond to equal or approximately equal intervals of temperature. The rate at which the temperature of the specimen is changing can in that way be observed, and any change of that rate—due to an evolution or absorption of heat within the specimen—can be noted and recorded.

The use of a simple moving-coil millivoltmeter, read by means of a pointer and scale, can hardly be regarded as adequate for anything more than a very rough approximation. The sensitiveness of such an instrument is necessarily low, and therefore, with moderate rates of cooling or heating, the pointer moves over the scale very slowly indeed. Only very well-marked thermal changes can therefore be detected by this method. When the millivoltmeter having a material pointer is replaced by a more sensitive reflecting galvanometer, the value of the method is multiplied several fold, since now the available length of scale becomes considerably larger and the motion of the spot of light, for a given rate of heating or cooling of the specimen, becomes correspondingly quicker. Here, however, two factors must be borne in mind which militate against the attainment of any very high degree of accuracy and sensitivity. In order that the indications of the galvanometer deflections may be translatable directly into thermal E.M.F. of the couple and thence into temperature, it is essential that the total resistance of the galvanometer circuit shall not vary appreciably during the entire heating and cooling operations. But the galvanometer circuit must, in this arrangement, include the couple wires themselves, and the temperature of these wires undergoes a large change. As the temperature coefficient of such wires is always high, their resistance will change very considerably, and if this is not to affect the value of the galvanometer readings, a large swamping resistance must be interposed in the circuit. Similarly, changes of room temperature will affect the resistance of the moving coil of the galvanometer itself, and this kind of variation must also be "swamped" by an added resistance made of a material having a very low temperature coefficient. All this involves that, although a fairly sensitive galvanometer may be used, its actual sensitivity must be cut down very materially by these added resistances. A second factor which causes some difficulty and is liable to introduce unsuspected inaccuracies is the tendency of many sensitive galvanometers to undergo slight changes of zero, particularly after a somewhat considerable deflection. The careful avoidance of excessive deflections therefore becomes important for work of this kind. The difficulty can be overcome in another way by using a galvanometer having a bi-filar suspension, and for purposes of direct deflection readings this is entirely satisfactory, since bi-filar galvanometers of sufficient sensitivity can be obtained for this purpose even after the introduction of the necessary "swamping" resistance.

(ii.) *The Potentiometer Method.*—There can be no doubt, however, that the degree of sensitivity and accuracy obtainable in such temperature observations can be very considerably increased by utilising the potentiometer for the determination of the E.M.F. of the thermo-couple. The ordinary, simple type of slide-wire potentiometer, however, is not well suited for this purpose, on account of the difficulty of following with such an instrument the varying E.M.F. of the couple during a cooling or heating operation. Ideally, it would be desirable to maintain the galvanometer constantly at zero by moving the slide-wire contact at precisely the rate demanded at each instant by the changing temperature of the couple. If this were done there would be no current flowing through the galvanometer circuit and the changes of resistance, whether in the thermo-couple wires or in the galvanometer coil, would become immaterial. It is, however, extremely difficult, if not impossible, to ensure this state of affairs in practice, because it is very difficult to follow exactly the changes of the E.M.F. of the couple by movements of the slide-wire contact made by hand in the ordinary way. The difficulty lies in the fact that it would become necessary to time the exact instants at which the potentiometer contact passes over successive points on the slide-wire corresponding to equal temperature (or E.M.F.) intervals. Consequently, any slight over-shooting of the mark, or failure to follow exactly, would lead to relatively large errors in the time observations. Since these observations are required to attain

an accuracy of 0·1 second for intervals of about 8 or 10 seconds, this difficulty becomes considerable.

A device has therefore been adopted which combines the convenience of observation afforded by the deflection method with the higher accuracy of measurement which the potentiometer affords. In this arrangement a more open galvanometer scale is employed than is possible with the simple deflection method, and when the galvanometer has reached the maximum deflection desired, it is brought back across the scale by means of the potentiometer, when it can begin a fresh series of deflections. This is accomplished by simply balancing a known portion of the E.M.F. of the thermo-couple by means of the potentiometer, leaving the remainder of the E.M.F. to produce a deflection. This combination of the two methods, however, introduces certain complications. In the first place, some of the disadvantages of the direct deflection method remain to be guarded against, such as shift of galvanometer zero and changes of sensitivity arising from temperature changes. The potentiometer circuits must therefore be so arranged that the galvanometer is always placed in series with a relatively large external resistance. It is further necessary to secure that the total resistance of the galvanometer circuit remains unaffected by any movement of the potentiometer contacts. With the ordinary form of slide-wire instrument this is not the case, and a special type of potentiometer must therefore be used. This type of instrument is indicated in the diagram (*Fig.* 3), where it will be seen that a change

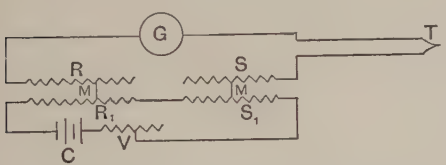

FIG. 3.—T = Thermo-couple. G = Galvanometer. R, R, and S, S_1 = Pairs of sets of Potentiometer Coils. M, M = Movable Potentiometer Contacts. C = Standard Cell, replaced in use by Accumulator adjusted, with variable resistance V, to give desired potentials in R_1, S_1.

in the position of the potentiometer contact throws into one branch of the galvanometer circuit a resistance exactly equal to that which has been taken out of the other branch.

Perhaps the most serious disadvantage of this type of apparatus lies in the difficulty of finding a satisfactory galvanometer which will allow of rapid movement from one end of the scale to the other within the short time available between two successive readings, and will yet possess sufficient constancy of zero and general stability to avoid disturbances in the next few readings after the change-over has been made. Even if a specially good galvanometer of the bi-filar type is used, there still appear to be some small forces at work for a few seconds after the galvanometer has been swung back across the scale, and for delicate observations it is usually found that one or two readings immediately after the change-over are more or less disturbed. For most purposes this is immaterial, since the origin of these disturbances, and the precise points where they occur, are well known. Sometimes, however, such a disturbance coincides with the beginning or end of a critical range, or with a small and doubtful critical point, and in those circumstances a whole series of observations may be vitiated. Various devices for avoiding this inconvenience have been proposed, but do not appear to have been put into practice up to the present time.

§ (5) RECORDING RESULTS. (i.) *Time Temperature Curve.*—Passing now to the methods of recording the results of series of time and temperature observations made during the heating or cooling of a specimen of metal, it is obvious that the simplest method of representing such data is to plot them in the form of a "time-temperature" curve, *i.e.* of a graph having time (t) as abscissæ and temperature (θ) as ordinate. Taking as an example the type of curve obtained from the cooling of a pure metal from a temperature above its melting-point, such a graph takes the form shown in *Fig.* 4 (*a*) for the case of "natural" cooling. The first branch of this curve represents the "natural" cooling, at a rapid but slightly diminishing rate, of liquid metal; the next branch is a horizontal portion or "platform" due to the period in which the metal is maintained at a constant temperature, in spite of continued loss of heat to its surroundings, owing to the freezing process and the consequent evolution of the latent heat of fusion. This horizontal portion is followed by a branch representing the further "natural" cooling of the solid metal. At first this is more rapid than it was just before freezing took place, because while the temperature of the metal has remained constant the crucible and furnace in which it is contained have continued to cool; a little later, however, the cooling process again slows down and becomes increasingly slower as the temperature falls.

If the metal has been cooled at a constant rate, by one of the devices described above, then the graph, plotted in the same manner as before, takes the form shown in *Fig.* 4 (*b*).

So long as it is sufficient to represent the results of such observations on a comparatively small scale, the method illustrated in *Fig.* 4 (*a*) and (*b*) remains satisfactory, but

when it is desired to employ a much larger scale, the simple time-temperature graph is no longer convenient or satisfactory. The use of a much larger scale, however, becomes essential if the high accuracy of the observations made by means of the potentiometric methods described above is to be reasonably utilised. Where observations are taken to an accuracy of the order of 0·1 second, an interval of one second requires to be represented by a length of at least one millimetre, or preferably by twice that amount. An ordinary series of cooling observations, however, frequently extends over a period of an hour and a half, so that with a scale of only

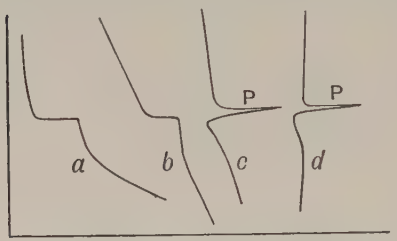

FIG. 4.—Time-temperature and Inverse-rate Curves.

one millimetre per second the abscissa of the curve would require a length of 5·4 metres. Such a graph would not only be inconvenient and unmanageable, but by its flatness would mask the smaller heat-evolutions, unless the temperature-scale were also extended in a corresponding measure.

(ii.) *Inverse-rate Curves.*—This difficulty, however, is at once overcome by plotting the data obtained not as a simple time-temperature (t/θ) curve, but as a "rate" or "inverse rate" curve ($(dt/d\theta)/\theta$). Such a graph represents the differential coefficient of the simple time-temperature graph, and has the very great advantage not only of compressing the curve into reasonable space without requiring a corresponding diminution of scale, but it also serves to accentuate minute irregularities in the curve itself. This accentuation, of course, is also applied to experimental errors, but in the best practice it has been found possible to eliminate these to a very large extent, so that the curves—apart from the critical points—are practically smooth, even when thus differentiated. The forms of the inverse-rate curves corresponding to the two time-temperature curves shown in *Fig.* 4 (*a*) and (*b*) are shown diagrammatically in the same figure at (*c*) and (*d*) respectively.

In practice, the plotting of the results of thermal observations in the form of the inverse-rate curves offers no difficulty. All that is required is a series of observations, not of the total time which has elapsed since the beginning of the series down to each particular temperature observed, but merely the interval of time which has elapsed for a given change of temperature. What is thus obtained is not, of course, strictly $dt/d\theta$ but rather $\Delta t/\Delta\theta$, where $\Delta\theta$ is a small and constant interval of temperature. This method of observing and plotting, not actual rates but finite times for finite temperature intervals, has the further advantage that it avoids infinite values for the inverse rate which would otherwise occur where—as at the points P, P in *Fig.* 4 (*c*) and (*d*)—the rate of change of temperature becomes zero. This very departure of the plotted observations from the theoretical shape of the graph, however, makes it evident that, in the vicinity of critical points at all events, the temperature intervals corresponding to successive time observations must be kept as short as conveniently possible.

§ (6) EXPERIMENTAL DETAILS.—The experimental means employed for obtaining the simple time-temperature curves are themselves very simple. Both the time-temperature curve and the inverse-rate curve derived from it can be plotted on squared paper in the ordinary way from time observations which have been recorded in any convenient manner. The times of transit of the galvanometer spot over scale-divisions representing successive temperature readings may be noted by simple observation on a good watch or clock, and with practice observations down to half a second or even less may be obtained in this way. By the use of two stop-watches (4) used alternately, one being started by the same movement which stops the other, somewhat better time data may be obtained. Finally, the times of transit may be recorded on an ordinary drum or tape chronograph by an observer who merely taps a key as each transit occurs. From data recorded in this way either the simple t/θ curve or the $(dt/d\theta)/\theta$ curve can be plotted, although the operation is laborious where a long series of observations has to be dealt with. The simple time-temperature curve, however, lends itself readily to autographic recording if a simple deflection method of measuring the temperature has been employed. For this purpose, Roberts-Austen (5) introduced a form of photographic recorder in which a photographic plate is moved vertically while the spot of light from the galvanometer passes across it horizontally with changing temperature. The resulting trace is then a simple t/θ graph. The photographic plate may be replaced by sensitive paper (photographic bromide paper) rolled on a drum which revolves at a slow and known rate. The use of the paper allows of a larger scale being employed, but even then the limitation

of size is a serious difficulty which makes it impossible to employ an open scale.

Another appliance for tracing time-temperature curves is that known as the Brearley Curve Tracer. Here again the simple direct deflection method of measurement is employed, but the spot of light from the galvanometer travels over a ground-glass scale. A pointer is provided which is kept immediately under the spot of light by the observer, who operates a traversing screw provided for that purpose; with this pointer travels a pen or pencil tracing a curve on paper attached to a drum which rotates, by clockwork, at a steady, known rate. While this appliance allows of the use of rather a longer scale than the photographic apparatus, it has the countervailing disadvantage that the accuracy of the resulting curve depends upon the skill and care with which the operator can keep the pointer constantly below the spot of light on the scale.

(i.) *Plotting Chronograph.*—So far as the inverse-rate curves are concerned, no method is as yet available whereby they can be recorded in an entirely autographic or automatic manner. The time and labour required for plotting such curves by hand from time observations registered on an ordinary chronograph can, however, be largely saved by the use of a special type of "Plotting Chronograph" which has been designed and constructed for this purpose (2). With this instrument the observer has merely to tap a key at each transit of the galvanometer spot over one of the divisions of the temperature scale; the instrument itself traces the inverse-rate curve in the form of a series of dots on a scale sufficiently large fully to utilise the sensitivity and accuracy of which the modern methods of thermal measurement are capable. The principle on which this instrument operates is as follows: The piece of paper on which the graph is to be plotted is fixed on a large drum, and across the surface of this drum, but without touching it, a pen is moved at a steady rate. The motion of the pen continues until the observer taps his key. As soon as this occurs, the pen is sharply depressed into contact with the paper on the drum, thus marking a point, and immediately afterwards the pen is returned by a rapid motion to its zero position, from which it again starts out on another journey across the drum. At the same time as the pen is returned to zero, the drum is advanced by a small step—these steps represent the temperature scale, each step being equivalent to one interval on the scale used by the observer. It will be seen that by this series of operations, each successive point is marked on the paper at a distance from the zero line which is proportional to the time which has elapsed since the previous tapping of the observer's key, so that the abscissa of the resulting graph is proportional to $\Delta\theta$, while the ordinate represents Δt. The mechanical and electrical devices whereby this operation is secured to a sufficient degree of accuracy cannot be described here, and reference must be made to the original paper in which the instrument is described. Such a plotting chronograph has now been in use for more than four years at the National Physical Laboratory and has proved eminently successful. A typical group of thermal curves as obtained by the combined use of the gradient furnace, the special type of potentiometer, and the plotting chronograph is shown on a very much reduced scale in *Fig.* 5.

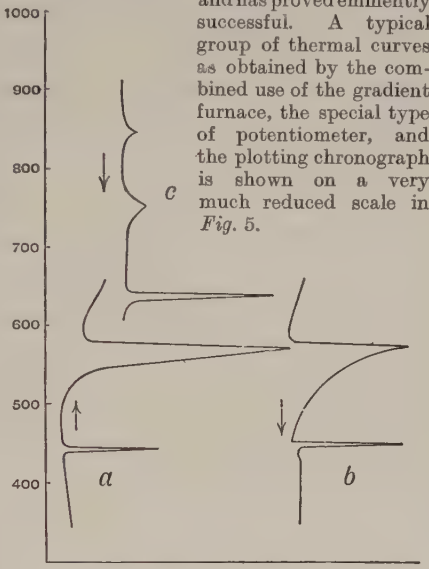

FIG. 5.—Typical Inverse-rate Heating and Cooling Curves.

§ (7) THE DIFFERENTIAL METHOD.—Before dealing with the physical interpretation which may be placed on the indications of thermal curves, it is desirable to refer to an entirely different method of obtaining such thermal data. This method, usually called the "Differential" method, of obtaining thermal curves was originated by Roberts-Austen (6). Both in regard to the simplicity of the apparatus employed and to the delicacy and accuracy of the observations which can be made by it, this method possesses certain distinct advantages. Indeed, unless the inverse-rate method is applied with every available advantage and refinement, it is probable that "differential" curves, and particularly the "derived differential" curves, are likely to yield better results.

The principle of Roberts-Austen's method consists in taking observations not of the time occupied by the cooling (or heating) specimen, but of the difference of temperature between the specimen under observation and a "neutral" body which is undergoing cooling

(or heating) at as nearly as possible the same average rate as the specimen. The manner in which this is done by means of three thermo-couples is indicated in the diagram (*Fig.* 6). Here S is the specimen under observation and N is the "neutral" body which is being heated or cooled with it. A "neutral" body in this sense is one consisting of some material which shows no evolution or absorption of heat within the range of temperature in which it is employed. A piece of platinum is often used, but other materials such as well-fired porcelain may also be employed. The temperature of the specimen S is measured directly by one thermo-couple, T_1, whose indications are read by means of the galvanometer G_1, generally with the aid of a potentiometer similar to that described in connection with inverse-rate curves. Two other thermo-couples, T_2 and T_3, are placed, one in the specimen S close to the couple T_1 but electrically insulated from it, and the other in the neutral body N. These two, the "differential"

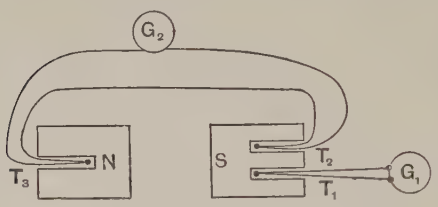

FIG. 6.—Diagram of the "Differential" Method.

couples, are connected together and to a galvanometer G_2 in such a manner as to be opposed to one another. So long, therefore, as the specimen and the neutral body are at the same temperature, there will be no deflection in the galvanometer G_2. As soon, however, as a difference of temperature is set up between S and N, a deflection is observed in G_2, and the amount of this deflection is, approximately at all events, proportional to the difference of temperature between the two "differential" couples, T_2 and T_3. If it were possible to heat or cool the specimen and the neutral body at precisely the same rate, no differences of temperature would occur until an evolution or absorption of heat took place in the specimen. As soon as such a thermal change did occur, however, a powerful deflection of the differential galvanometer G_2 would occur. In practice it is never possible to secure that two bodies of different material, and therefore of different physical properties, shall change in temperature at precisely the same rate, even when heated or cooled side by side in the same furnace. A certain divergence of temperature of the two bodies, therefore, always occurs, and this brings about a gradual and steady deflection of the galvanometer G_2. As soon as a thermal change occurs, however, there is a marked change in the rate and sometimes even in the direction of this deflection, and from these "abnormal" deflections it is comparatively easy to subtract the normal and steady deflection due to the cause already indicated.

In practice, it is usual to arrange that the spots of light from both G_1 and G_2 move across the same scale, but G_1 moves rapidly and is brought back across the scale from time to time by means of the potentiometer, while G_2 moves as a rule much more slowly until a critical point is reached. The observations are easily taken, after a little practice, by noting, for each transit of the spot from G_1 across one of the main divisions of the scale, the position of the spot from G_2. This yields a series of readings which represent the difference of temperature between T_2 and T_3, that is between the specimen and the neutral body for each selected temperature. These readings can then be plotted on squared paper to any desired scale and yield what is known as a "differential curve." Where it is possible to prevent the difference of temperature between S and N from becoming large except at the critical points, such a curve would offer a fairly satisfactory picture of the thermal changes undergone by the specimen, showing a "bulge" or peak, more or less well-defined, corresponding to each evolution or absorption of heat. If, however, the temperature of the two bodies diverges to any considerable extent, these peaks become superposed on a graph which is not only strongly inclined to the vertical, but which may vary somewhat in inclination if the curve is followed over any wide range of temperature: such a variation of slope is, in fact, inevitable if the physical properties of the two bodies, such as specific heat, thermal emissivity, etc., do not vary with temperature according to the same law in the two bodies. Where smaller thermal changes are to be traced, these variations become very troublesome, and a modification of the method of plotting has accordingly been suggested and used with advantage (7). This consists in plotting against the temperature of the specimen as indicated by readings of G_1 not the actual deflection of G_2, but merely the change which that deflection has undergone since the previous reading. The resulting graph is, of course, a representation of the differential coefficient of the plain "differential" curve. Any steady slope or even gradual change of slope of the primary curve becomes obliterated, and the smallest "bulges" in which the primary curve departs from its normal course stand out as definite peaks on the "derived differential" curve plotted in the manner

indicated. We shall see below that this derived curve bears precisely the same relation to the plain differential curve as does the inverse-rate curve to the plain time-temperature curve. Typical examples of a differential and a corresponding "derived differential"

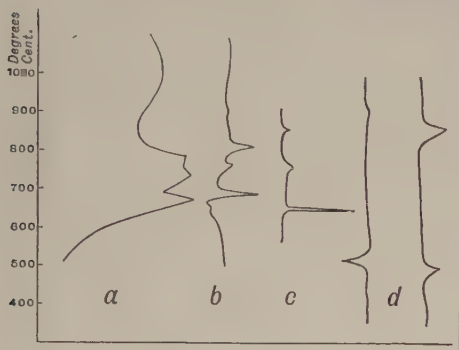

FIG. 7.—Typical "Differential" and "Derived Differential" Curves.

cooling curve of a mild steel are given in *Fig.* 7 (*a*) and (*b*).

§ (8) PHYSICAL INTERPRETATION.—For the physical interpretation of the data contained in thermal curves, it is desirable to revert in the first instance to the fundamental time-temperature curve, and for the sake of simplicity we may confine our attention to the case of cooling curves, although the conclusions reached will apply, subject to necessary changes of sign, to heating curves also.

(i.) *Time-temperature Method.*—Let ARC (*Fig.* 8) represent diagrammatically the cooling curve, plotted with temperatures θ as ordinates and times t as abscissae. The hump on this curve represents a small evolution of heat. In the absence of this evolution of heat, we know that the cooling would have continued along the dotted curve ABC; this latter is, in fact, the cooling curve of an ideal neutral body having the same physical constants as the specimen under observation, but free from all thermal changes. In order further to simplify matters, let it be supposed that the total time occupied by the small heat evolution is so short that the curve ABC may be regarded as a straight line throughout that interval. The slope of that curve then represents the rate of loss of heat from the equivalent neutral body at the time of the heat evolution. If we now make the further assumption that throughout the short time in question the specimen is losing heat at the same rate as the ideal equivalent neutral body, follows that the quantity of heat which has been liberated or "evolved" in the specimen is proportional to the greatest vertical distance between the two curves ARC and ABC. That this is the case will be readily seen by considering the extreme case of a body which is losing heat at a negligibly slow rate; the curve ABC then becomes a horizontal straight line, while, on the addition of heat to the body, the curve ARC would rise vertically by an amount (BR) proportional to the quantity of heat supplied. In the case of a body losing heat at a constant rate we may approximately write "excess of temperature" in place of "rise of temperature" as in the adiabatic case.

In practice, however, two errors corresponding to departure from the conditions assumed above make themselves felt to a serious extent. In the first place if the evolution of heat occurs over a considerable period of time—as it often does when the heat is not all evolved at a single temperature but over a range—then the rate of cooling can no longer be regarded as constant throughout the time in question. In the second place, during the time corresponding to that part of the curve lying between A and R the rate at which the specimen is giving out heat is no longer identical with the rate which corresponds to the conditions of point A. At the latter point, the specimen is still cooling uniformly with its immediate surroundings, *i.e.* the furnace, etc. As soon,

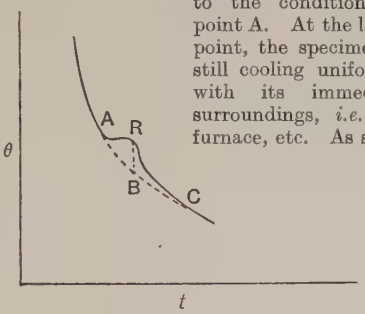

FIG. 8.

however, as the fall in temperature of the specimen is arrested, a difference of temperature is set up between it and its immediate environment, and this results in a loss of heat from the specimen at a greater rate than that of the ideal equivalent neutral body. Both these departures from the assumed conditions tend to render the line BR shorter than it should be if strictly proportional to the quantity of heat liberated. A full discussion of the phenomenon, however, should include a number of other conditions, such as the effect on the temperature of the furnace brought about by the heat liberated in the specimen. Without going further into the matter it may be concluded that while the shape of the time-temperature curve gives an approximate indication of the quantity of heat liberated in

any thermal change and also gives indications of the speed with which it is liberated, it is by no means easy to interpret such curves quantitatively.

(ii.) *Inverse-rate Method.*—Turning now to the inverse-rate curve, let LMN (*Fig.* 9) be such a curve, plotted with temperature θ as ordinate and $dt/d\theta$ as abscissa. The area enclosed by an infinitesimal element of this curve and its

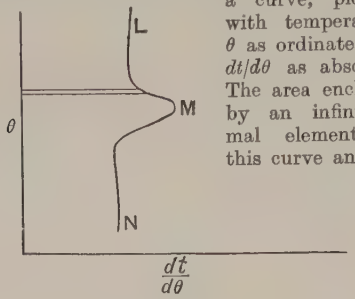

FIG. 9.

corresponding abscissa on the axis of θ is given by $dt/d\theta \cdot d\theta$. Therefore the area enclosed by the curve and the axis of θ over the temperature-range from θ_a to θ_b is

$$\int_a^b \frac{dt}{d\theta} d\theta$$

and the value of this integral is

$$t_b - t_a.$$

The area, therefore, represents the time which has elapsed during the cooling of the body from the temperature θ_a to the temperature θ_b. If we find the value of this time, both for the body which is undergoing a thermal transformation and for an equivalent ideal neutral body cooling through the same temperature range under identical conditions, the difference in the times found represents the retardation in the time of cooling, which has been brought about by the evolution of heat in the body under observation. This retardation in time, measured by the rate of loss of heat—assumed identical in both bodies—measures the difference between the quantity of heat lost by the specimen under experiment and the ideal neutral body; this excess of heat is obviously the quantity of heat evolved during the thermal transformation in question.

The above analysis suggests that an accurately observed and plotted inverse-rate curve should furnish much useful information. The difficulty, however, of knowing the real rate of loss of heat brings with it severe limitations, and introduces exactly the same order of errors as those already discussed in connection with the interpretation of the time-temperature curves. A further difficulty consists in deciding between what precise limits this time-interval, *i.e.* the area of the peak in the curve, is to be measured. The correct limits should correspond to the precise beginning and end of the heat evolution. Even the beginning of the heat-evolution is not entirely definitely marked, but the end is decidedly vague. During the progress of the heat evolution, the temperature of the specimen lags behind that of its surroundings, which continue to cool; consequently, as soon as the heat-evolution ceases, the specimen begins to cool much more rapidly. Ultimately, if the cooling is continued long enough, the specimen must regain thermal equilibrium with its surroundings. The result, on a time-temperature curve, is a steep portion following the "platform" corresponding to the thermal arrest, while on the inverse-rate curve the effect is seen by a backward sweep of the curve which temporarily approaches much closer to the axis of θ than in the normal parts of the curve. If the time, $t_b - t_a$, is taken over too wide a range, therefore, this temporary accelerated cooling materially affects the result. The choice of the exact limits between which the area of the peak shall be measured in such a curve as that of *Fig.* 9, therefore, becomes of great importance. It will not be correct to consider that the thermal change is at an end when the rate of fall of temperature of the body under observation again becomes equal to that of the ideal equivalent neutral body, because at that stage the specimen is still hotter than the equivalent body, and is therefore still receiving a supply of heat from the internal evolution—otherwise it would be cooling faster. The end of the heat-evolution, therefore, lies just beyond this point, where the ideal "blank" curve crosses the observed curve. The precise location of this point can only be estimated in any given observed thermal curve by the judgment of the observer, and therefore a serious element of uncertainty is unavoidably introduced into all quantitative interpretations of such curves. None the less, where the curves are plotted on an open scale from observations of sufficient accuracy, and where the mass of the body under observation is not too small, reasonably good estimates of the quantities of heat evolved at various critical points can be made, and fairly satisfactory data as to the relative intensities of the thermal changes in a series of alloys can be obtained.

For all such estimates and comparisons, however, it is—as has been indicated above—fundamentally important to know the rate of cooling. Ideally, it is desirable to know the rate of cooling of the equivalent neutral body, but for the comparison of the peaks in a series of curves from a group of alloys, or even for the comparison of various peaks occurring successively on the same curve, it

is sufficient if we can be sure that the rate of cooling has been constant. It has been pointed out above that when specimens under thermal observations are allowed to cool "naturally," no constancy of rate can be secured. It is one of the main advantages which are secured by the use of the "gradient" furnaces that such constancy can be ensured. With these furnaces, provided that careful attention is given to the mass of the specimen, and also to the maintenance of constancy of all other conditions, comparative quantitative data of considerable accuracy can be obtained. The importance of such data lies in their application to the process of so-called "thermal analysis," which is dealt with elsewhere (see article on "Alloys, the Equilibrium Diagram").

Beyond the approximate proportionality of the area of a peak on an inverse-rate curve to the quantity of heat evolved (or absorbed), the shape of the peak affords some further information. Reverting for a moment to the simple time-temperature curve, we have seen that at any instant the length of the line BR —the vertical distance between the observed curve and the ideal blank—represents approximately the quantity of heat generated in the body under observation, and therefore the rate of change of this length measures the rate of evolution of heat. This rate of change of vertical distance, however, is simply the difference of slope of the two curves, *i.e.* of the observed curve and of the ideal blank. If we assume that the slope of the ideal blank is constant during the heat evolution, this difference becomes proportional to the slope of the observed time-temperature curve. But the slope of the observed curve is the rate of cooling of the body and its inverse is the "inverse rate," $dt/d\theta$, which is plotted in the inverse-rate curve. Now, the smaller the slope of the time-temperature curve, the greater the rate of heat-evolution which it represents; therefore a *maximum* on the inverse-rate curve will indicate a maximum rate of evolution of heat and—to a certain degree of approximation—the maximum deflection, or "height of apex" of a peak on the inverse-rate curve, will be proportional to the rate of evolution of heat.

(iii.) *The Differential Method.*—Consideration of the physical meaning of the curves obtained by the differential method leads to a series of interpretations very similar to those already arrived at for time-temperature and inverse-rate curves. In the differential method no time observations are taken; what is actually measured at each temperature of observation is the difference in temperature between the body under observation and a second body which may be regarded as a physical approximation to the "ideal neutral body cooling at the same rate," to which frequent reference has already been made. Actually, however, the physical neutral body is not ideal in that it unavoidably possesses physical constants different from those of the body under observation, and an identical rate of cooling or heating cannot as a rule be secured. The resulting state of affairs is indicated in the diagram, *Fig.* 10 (*a*), where ABC and A′, B′, C′ are the time-temperature curves of two cooling bodies, the former the body under observation, which undergoes a thermal change, while the latter is a "neutral" body free from such phenomena. The observations taken with the differential galvanometer measure the length of the lines AA′, BB′, CC′ at short and regular intervals of temperature. When these are plotted as abscissae against temperature as ordinate, the resulting curve—the "differential" curve—will take a shape like that of curve (*b*) in the diagram, *Fig.* 10.

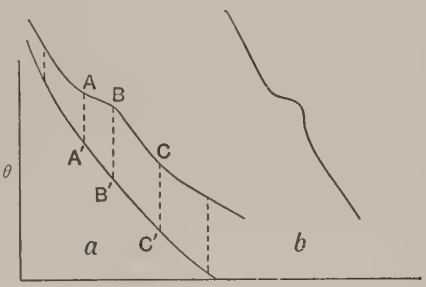

FIG. 10.

This curve shows a steady slope in one direction due to the gradual divergence of the temperatures of the two bodies, and upon this the peak due to the heat-evolution is superposed.

If the heat-evolution takes place over a range of temperature short enough to justify the assumption that over the range in question the vertical distance between the two curves, apart from the recalescence, has not varied appreciably, then the height of the peak of the differential curve represents a quantity which has precisely the same meaning as the length of the line BR (*Fig.* 8), plus a quantity which is simply the mean difference in temperature between the ideal neutral body and its actual representative. The interpretation of the differential curve thus corresponds very closely to that of the simple time-temperature curve; and this will be readily understood if it is realised that the only difference between the two types of curves lies in the fact that while in one case the temperature of the body under observation is plotted in regard to time directly determined by a clock, in the other it is plotted in regard to the temperature

of a body whose temperature is changing steadily, so that the temperature changes are proportional to time, particularly over the short ranges to which our discussion has been confined.

In consequence of this similarity of physical meaning, the differential curve shares many of the disadvantages of the time-temperature curve. These make themselves felt more particularly when the slope of the differential curve becomes considerable, as the result of too great a difference in the rates of cooling or heating of the two bodies. These difficulties can be overcome by the use of the "derived differential" curves already referred to above. These curves are very similar in appearance to the corresponding inverse-rate curves and, again, bear a closely similar physical interpretation.

Referring again to the fundamental time-temperature curves of the two bodies as shown in *Fig.* 10 (*a*), we may write the equations of those curves as

$$\theta_1 = f(t) \text{ and } \theta_2 = \mathrm{F}(t),$$

where $f(t)$ and $\mathrm{F}(t)$ are two different but unknown functions of t, except that in the case of a constant rate of cooling, $f(t)$, which represents the cooling-curve of the neutral body, takes the simple form

$$\theta_1 = kt,$$

where k is a constant.

The abscissae of the ordinary or first ("differential") curve are the values of $\theta_2 - \theta_1$ for various values of θ, and we have

$$\theta_2 - \theta_1 = \mathrm{F}(t) - f(t) = \mathrm{R}.$$

Calling this R, we have

$$\frac{d\mathrm{R}}{d\theta_2} = 1 - f'(t)\frac{dt}{d\theta_2},$$

where $f'(t)$ is the differential coefficient of $f(t)$ with respect to t.

Now $d\mathrm{R}/d\theta_2$ is the quantity which is plotted as abscissa in the derived differential curve. For a constant rate of cooling, for which $f(t)$ becomes either unity or a constant, the quantity $d\mathrm{R}/d\theta_2$, plotted against θ in the derived differential curve, becomes a linear function of the quantity $dt/d\theta_2$, which is the quantity plotted in the inverse-rate curve.

In the derived differential curve, the area of a peak is given by the integral

$$\int \frac{d\mathrm{R}}{d\theta_2} d\theta_2,$$

and this is equal to R between the limits of the beginning and end of the heat-evolution. R, as we have seen, measures the quantity of heat evolved, so that with the same limitations as already indicated for the inverse-rate curves, the area of a peak on the derived differential curve is also proportional to the heat evolved by the thermal change. The rate of cooling is supposed known and taken into account in both cases, since this factor affects both types of curves to much the same extent. Further, the area of the peak must be measured to that point which represents the end of the heat evolution, and this is quite as difficult to ascertain in the derived differential as in the inverse-rate curves.

§ (9) Typical Curves.—Examples of some typical thermal curves, taken by both the inverse-rate and the differential method, are shown on a very much reduced scale in *Figs.* 5 and 7, already referred to above. Curves (*a*) and (*b*), *Fig.* 5, are reduced from inverse-rate heating and cooling curves respectively, obtained with the gradient furnace, potentiometer, and plotting chronograph; they relate to an alloy containing aluminium 74 per cent, magnesium 20 per cent, and silicon 6 per cent, and include the melting-point of the alloy. *Fig.* 5 (*c*) is the inverse-rate cooling curve of a mild steel, containing about 0·20 per cent of carbon, also taken by means of the special appliances just mentioned. In *Fig.* 7 (*a*) and (*b*) are given the ordinary "differential" and the derived differential cooling curves of a mild steel containing slightly more carbon than the sample to which curve (*c*) of *Fig.* 5 relates. For purposes of comparison, however, the inverse-rate curve, *Fig.* 5 (*c*), has been placed beside the derived differential curve of *Fig.* 7 (*b*), and reduced to the same scale, in *Fig.* 7 (*c*). Finally, the two curves of *Fig.* 7 (*d*) are derived differential heating and cooling curves of an alloy containing copper 88 per cent, aluminium 9 per cent, manganese 3 per cent. These curves, of course, do not include the melting-point of this alloy, which occurs at a very much higher temperature.

A comparison of these curves, particularly when plotted to a larger scale, shows that there is a very great degree of similarity between the results obtained by the two methods, and it would almost seem to be an open question which of the two is to be preferred. It will be noticed, however, that the differential curves relate to relatively small thermal changes which occur in solid metal—*i.e.* at temperatures below the freezing-point. This circumstance arises from one of the practical limitations which apply to the differential method, but not to the inverse-rate method. Where the piece of metal under observation passes through a large thermal change, such as that which occurs at the "liquidus" or on passing through the freezing-point of a eutectic, it becomes difficult to

follow the temperature changes by means of the differential thermo-couple. As a consequence of a large evolution of heat, a very large difference of temperature is set up between the specimen and the neutral body, with the result that there is a correspondingly large deflection of the differential galvanometer. If this is a sensitive galvanometer, such as is required for the purpose of showing small evolutions of heat, the spot of light is driven completely off the scale and the deflection of the galvanometer cannot then be read—even if the instrument can safely be exposed to it—without additional appliances, such as a potentiometer for balancing part of the E.M.F. of the differential couple, etc. If such appliances are added, however, the advantage of the relative simplicity of the differential method is to a large extent lost, while the use of such means of regulating the deflection of the galvanometer tends to introduce irregularities into the resulting curves. Further, when the difference of temperature between the specimen of metal under observation and the neutral body becomes large, the entire meaning of the "differential" curves becomes doubtful.

For the reasons just indicated, the inverse-rate method is generally used wherever observations include large thermal changes. For many purposes, however, it is inconvenient to take two kinds of curve for the same specimen — one to determine the freezing-point and another for observing thermal changes of less intensity occurring after solidification. There is, therefore, a natural tendency to use the inverse-rate method throughout, provided that it can be rendered sufficiently delicate and convenient. Thanks to the appliances which have been developed in recent years, and particularly to the plotting chronograph, this result has been attained. There can be no doubt, however, that for some purposes, and particularly for the detection and location of very small thermal changes, the differential method offers important advantages, so that for research purposes the use of both methods is desirable.

W. R.

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METALS AND ALLOYS, THE MICRO-STRUCTURE OF

A STUDY of the micro-structure of metal was first undertaken by Henry Clifton Sorby, of Sheffield, about the year 1864. Sorby applied the methods of microscopic petrography to the study of steel and at once found a complexity of structure and diversity of behaviour that served to show how fruitful a field he had touched. On the other hand, the structures met with in steel are so complex that any real insight into their meaning could hardly be obtained until simpler structures had been studied and mastered. It was, perhaps, partly for that reason that Sorby's work was not pursued for many years, until, in fact, the study of the micro-structure of metals was taken up independently, and in ignorance of Sorby's work, by Osmond in France and Martens in Germany. Soon afterwards a much wider development began, in which Roberts-Austen, Stead, and Arnold in England, and Howe in America took an early and important part. To-day the importance of the subject is fully recognised, not only on account of the very great practical value of the insight which it affords into the nature of metals, but also from the point of view of the physical proximate structure of metals, which are to be regarded as the simplest of solid bodies.

The manner in which samples of metals are prepared for microscopic examination by polishing and etching, and also the special types of microscope and of illumination employed in examining them, have been described in another article.[1] We may begin, therefore, by considering the structure which is observed when a specimen of a pure metal is viewed under a moderate magnification in a suitable microscope. Nor need we trouble, for this purpose, to secure samples of metal of very extreme purity, although in a more detailed examination the influence even of minor impurities must be considered.

§ (1) THE STRUCTURE OF A PURE METAL.—The structure seen when a piece of nearly pure iron is viewed under a magnification of 150 diameters is illustrated in *Fig.* 1. The surface of the specimen is seen to be covered with a species of irregular reticulation, dividing it into a number of more or less polygonal areas of varying shapes and sizes. This appearance at once suggests that the metal is an aggregate of grains of some kind, the black lines forming the boundaries of the little areas being simply the lines of junction of adjacent grains. A section through an aggregate of grains of irregular shape would, in fact, furnish just such a pattern as that

[1] "Metals, Microscopic Examination of."

illustrated. It has, however, been very conclusively shown that the grains of which pure iron—and indeed every pure metal—consists are in reality true crystals. It is obvious that they do not possess the regular geometrical outlines found in typical crystals which have been permitted free development; on the contrary, the boundaries of the crystals in a metal are merely the surfaces upon which adjacent crystals have met in the process of growth during their formation. The interior structure of each grain, however, is truly crystalline, in the sense that within each grain there is a uniform geometrical orientation, but this orientation differs in direction from one grain to another.

The evidence in support of this view is so strong that the crystalline nature of metal has come to be regarded as almost self-evident. The microscope itself affords very striking proofs. In the first place, a polished and etched specimen of pure metal exhibits a peculiar feature when viewed under obliquely reflected light which is sometimes known as an "oriented lustre." When the structure of the metal is minute this feature can only be seen under moderate magnifications, but where larger crystals have been formed they exhibit it to the unaided eye under suitable conditions. Seen under oblique illumination, such an etched surface shows certain of the grains to be brilliantly illuminated while others are completely dark. If the angle of incidence of the light is changed, either by moving the beam of light or by rotating the specimen, the appearance of the surface undergoes changes, grains which appeared brightly illuminated now becoming dark, while other grains flash up brilliantly. The appearance of such a surface, in a single position, is shown in *Fig.* 2, but the true character of the phenomenon can only be realised when movement takes place, unless the surface is simultaneously illuminated by a number of beams of light of different colours. In those circumstances, the various grains each reflect one of the coloured beams, according to the angle of incidence, and the surface appears covered with brightly coloured areas sharply distinguished from one another. When the surface is rotated under such multiple coloured illumination, a brilliant display of changing colours is obtained.

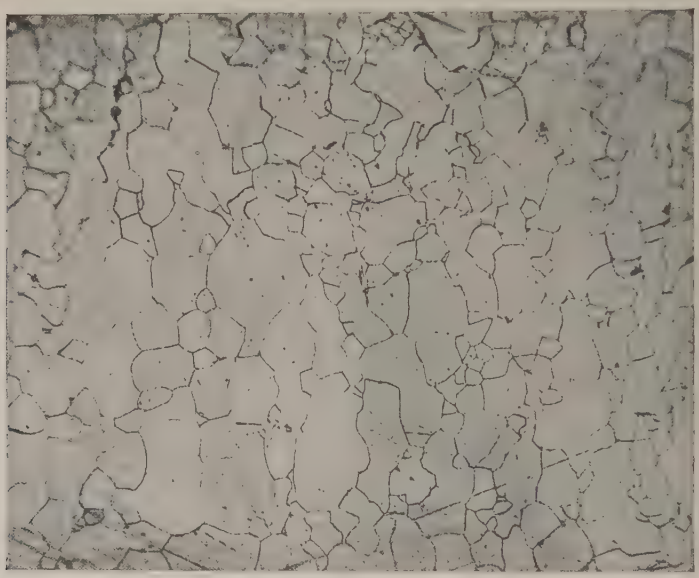

FIG. 1.—Pure Iron. ×150.

The cause of this "oriented lustre" lies in the varying orientation of the crystals which constitute the grains of metal. The process of etching which has been applied during the preparation of the surface has entailed a slight amount of dissolution of the metal in the etching reagent (usually a weak acid). The very development of the micro-structure by such an etching process shows that the chemical attack has not been uniform—some of the grains have been more strongly attacked than others, with the result that slight differences of level have been produced, giving rise to little steps from the surface of one grain to the next. Beyond this, however, the attack

on each grain has to some degree revealed the inner texture of the grain itself. The process of solution takes the form of a gradual unbuilding of the grain. It is much as if a well-arranged stack of bricks were being unbuilt by the removal of whole bricks or batches of bricks — the resulting surface would be stepped and terraced in a manner clearly corresponding to the internal orientation of the stack. Similarly the etched surface of a metallic grain or crystal is left stepped and terraced; it is, in fact, covered with minute facets which are strictly co-oriented within the same crystal, but vary in shape and orientation from one crystal to another. These bright little facets of metal furnish the reflecting surfaces which give rise to the phenomenon of "oriented lustre" described above.

FIG. 2.—Aluminium (Oblique Illumination). ×15.

In many cases, where the crystals themselves are small and where etching is not carried very far, these facets are too minute to be readily seen, even under high magnifications. In other cases, however, they are large enough to be clearly visible under moderate magnifications. An example, representing a specimen of silicon steel containing about 4 per cent silicon, under a magnification of 35 diameters, is shown in *Fig.* 3.[1] Where these facets are well developed they take a form very similar to the well-known "etch figures" found on mineral crystals, and they can then be utilised in the corresponding manner for a determination of the geometrical constants of the crystal in question. Evidence of this kind corroborates the view based on measurements of isolated crystals, that the majority of metals crystallise in the cubic system; a few, however, including zinc, cadmium, bismuth, magnesium, and tin, depart from this rule.

The truly crystalline character of metals has recently received striking confirmation from the application of the methods of X-ray analysis, as worked out by Laue, Bragg, and Hull. The evidence obtained by these methods leaves no room for doubt that the grains which constitute pure metals are essentially crystalline in character, having their atoms arranged on space-lattices in the way which is necessary to produce the typical diffraction of X-rays. The application of the methods of X-ray spectrometry to the study of metallic crystals offers the promise of a greatly increased insight into the internal structure of metals and the changes which this structure is liable to undergo, although certain serious experimental difficulties have yet to be overcome before the method can be directly applied to the more difficult problems.

Another line of experimental evidence which serves as strong confirmation of the truly crystalline character of metals is derived from their behaviour under strain or plastic deformation. This whole subject is specially treated

[1] Photographed by Dr. J. E. Stead, F.R.S., and reproduced by his kind permission.

elsewhere (see art. "Metals, Relations of Strain and Structure"), so that only brief reference is required here. It should be borne in mind, however, that the manner in which the grains of metal undergo plastic deformation by a process of internal slipping or sliding requires the existence of a perfectly oriented and regular structure within the grains, so that their behaviour can only be accounted for by regarding the grains as truly crystalline. The formation of what are known as twinned crystals is another evidence of the same kind. In regard to twinning, metals exhibit phenomena so strictly analogous to those with which we are familiar in typically crystalline minerals that a similarity of internal structure may safely be inferred.

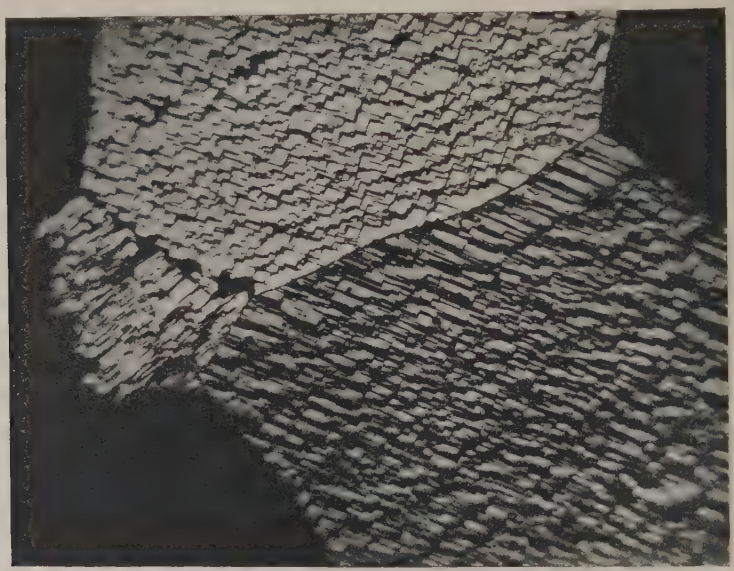

Fig. 3.—Etched Facets on Silicon Steel. ×35.

§ (2) Crystal Growth.—The manner in which the crystalline structure of a metal, such as we see illustrated in *Fig.* 1, is produced must now be considered. The simplest case for consideration is that of a pure metal solidifying from fusion during gradual cooling. In such cases it is found that crystallisation commences at a number of centres and that the minute crystals rapidly grow in size. These centres of crystallisation are usually spoken of as "nuclei," but it is not known what the nature of a crystal "nucleus" really is. On one view it has been suggested that when a metal is melted the crystalline aggregation of its atoms is not necessarily destroyed completely, and that the resulting liquid may well consist of a kind of colloidal suspension of fine particles of crystalline metal in a matrix of true liquid. With rising temperature it might be anticipated that these suspended groups would be broken up to an increasing extent and that at very high temperatures they might disappear entirely. If these minute oriented groups are to be regarded as the real nuclei from which crystallisation commences when the temperature falls to or below the freezing-point, then it would be anticipated that metal which had been carefully cooled from a temperature high above its melting-point would display little tendency to crystallise and might therefore be considerably undercooled. No conclusive evidence in support of such a view has yet been obtained; it is, however, well known that those metals which have a fairly low melting-point are also those in which undercooling is most frequently met, as for instance in lead and tin.[1] It is, of course, these metals which are most liable to be severely superheated.

A somewhat different light is thrown upon this matter by the observation that the purity of a metal appears to exert a powerful influence on the presence or formation of crystal nuclei. Very pure metals display an undoubted tendency to the formation of larger, and therefore fewer, crystals than where appreciable amounts of impurity are present. It is difficult to see why minute groups of oriented atoms should exhibit greater persistence in the presence of impurities than

[1] Roberts-Austen, "Surfusion in Metals and Alloys," *Roy. Soc. Proc.*, 1898, lxiii. 447-454.

in their absence, so that it is evident that the whole question requires further systematic investigation.

Whatever their origin or nature, crystal nuclei do not make themselves felt until any particular portion of metal has cooled at least to the temperature of the "freezing-point." In any mass of metal of appreciable size this temperature is not simultaneously reached throughout the mass, and consequently crystal nuclei appear in various regions successively as they cool. Usually cooling takes place from the exterior, and consequently crystallisation commences from the outer skin of a cooling mass of metal. The crystals which commence to grow outward in all directions from each nucleus, however, soon meet with their neighbours in the directions which lie parallel to the outer or cooling surface; growth in a direction at right angles to the cooling surface, however, cannot be hampered by the competition of neighbours, and as cooling progresses the growing crystals increase in length inwards from the surface.

This whole process may be more accurately expressed by the statement that crystal growth always occurs, in a metal cooling from the molten state, at right angles to the isothermals as they exist at any moment in the cooling mass. In the direction of any isothermal, there are always many competing and interfering nuclei or crystals emanating from them, but this is not the case in the direction perpendicular to the isothermals. The result is the formation of a structure consisting of radial crystals running inward from the outer surface of a piece of cast metal. In certain circumstances this gives rise to peculiar types of weakness, particularly near re-entrant corners in castings, but the applications of this principle to foundry practice cannot be pursued here.

The formation of such radial or inward-growing crystals requires, however, the existence of a fairly steep temperature gradient. If, therefore, cooling is somewhat slow, a different type of structure may be produced. In such circumstances a large number of nuclei may be formed or become active throughout a considerable zone of metal in which the temperature gradient is only slight—in such circumstances the growth of the older crystals may not have gone very far before new crystal centres start into activity all around them. Where this is the case, the growing crystals meet with the competition of their neighbours in all directions, there is no longer any direction of favoured growth, and the resulting crystals tend to become of approximately similar dimensions in all directions, or "equi-axed" as it is termed. When a considerable mass of molten metal is poured into a cold metal mould, the first stages of solidification follow the law of growth at right angles to the isothermals. The rapid liberation of the latent heat of fusion, however, soon retards the rate of cooling of the liquid interior of the mass, and after a time the temperature gradients become small enough to allow the crystallisation to finish with the formation of a core of equi-axed crystals. In recognition of these facts the outer zone of radial crystals is generally called the zone of "chill" crystals.

The exact manner in which a crystal will grow outward in a cooling mass of molten metal when its formation has been begun at a centre or nucleus varies considerably in different metals and even in the same metal according to circumstances. Rate of cooling, and therefore of crystallisation, is probably the most important factor, but the presence or absence of impurities (or alloying elements) also plays an important part. It is probably only quite rarely that the crystals of a metal grow in a regular manner, layer by layer, in the fashion with which we are familiar in the slow crystallisation of many salts from their solutions. The marked absence of geometrical outlines in most metals is strong evidence for this view. In the case of inter-metallic compounds, however, where the crystals frequently grow in a liquid medium having a lower freezing-point, such geometrical growth is much more frequent. In these cases, however, there appears to be a remarkable tendency for the production of hollow, shell-like forms rather than solid geometrical crystals. All the evidence points to the view that, in the very great majority of cases, the growth of metallic crystals occurs by the formation of dendrites or branched forms which only become filled up as the process of solidification becomes completed. In pure metals like lead, tin, or antimony, it is quite easy to show, by rapidly draining off the liquid residue from a partially solidified mass, that the crystals were growing dendritically, and the micro-structure of many alloys confirms this conclusion. A beautiful example of such dendritic structure is shown in *Fig.* 4, which represents a crystallite of silver formed in a matrix of an alloy of silver and copper.

The process of dendritic growth is of very considerable importance in its subsequent effects on the structure of a metal. We shall see below how important a part it plays in determining the structure of those alloys which form "solid solutions," but even apart from those it may determine a feature which no subsequent treatment of the metal can completely eradicate. Thus in all kinds of steel, however much mechanical working or heat treatment they may have undergone, it is possible, by suitable means of examination, to trace structures which are the direct

representatives of the original dendritic crystals which were formed when first the molten steel solidified in the ingot-mould. Usually these persistent effects are due to the fact that the growing dendrites bring about a particular distribution of any impurities which may be present. If the impurities are of such a nature as to remain in the crystallised material without separating out into special micro-constituents, the growing dendrites still bring about a concentration of the impurities in the outer regions and in the "bays" between the branches of the dendrite. On the other hand, impurities which are either

Fig. 4.—Dendrite in Silver-copper Alloy. ×150.

mere mechanical enclosures, or which separate out as distinct constituents, are usually pushed outward by the growing dendrites, and are thus forced into the crystal boundaries, or they may be "trapped" between the growing branches of the crystal. In this latter case, their presence serves to outline the contours of the original dendrite, and these contours may remain visible in this way long after the entire crystalline structure has been swept away and replaced by an entirely different one as the result of work or of heat treatment.

§ (3) Effect of Cooling.—We have now to consider the changes which the crystalline structure of a metal may undergo subsequent to its first formation on cooling from the liquid state. The effects of mechanical deformation, whether applied to the metal while hot or cold, will not be considered in detail here, as they are more fully referred to in other articles (see "Metals, The Relations of Strain and Structure," and "Metals, Thermal and Mechanical Treatment"). The processes with which we are concerned here are mainly those known as "recrystallisation" and "crystal growth." An endeavour has recently been made to draw a sharp distinction between these two processes,[1] but it seems doubtful whether any such distinction is justified, since any recrystallisation necessarily occurs by the formation, and therefore the growth, of fresh crystalline material.

When a pure metal, on cooling from fusion, has developed its typical structure, consisting of an aggregate of crystalline grains, there is considerable reason to believe that, in the absence of either mechanical deformation or of internal or "allotropic" transformations, it is difficult, if not entirely impossible, to bring about any rearrangement of the structure.[2] In the extreme case where the molten metal has been cooled very rapidly, and the resulting crystalline structure is very minute, even prolonged heating at temperatures well above those at which recrystallisation occurs readily and rapidly in metal only slightly strained, produces no effect on the structure. Whether it is safe to generalise upon the limited experi-

[1] Carpenter and Elam, "Crystal Growth and Recrystallisation in Metals," *Journ. Inst. Metals*, 1920, ii.

[2] Ewing and Rosenhain, "The Crystalline Structure of Metals," second paper, *Roy. Soc. Phil. Trans.* A, 1900, cxciii.

mental evidence available and to draw the conclusion that the structure of a cast metal, in the absence of special causes, is too stable to be affected by heat treatment, must remain to be seen; so far there is, at all events, no definite evidence to the contrary.

§ (4) Allotropic Forms.—In the case of a metal undergoing an allotropic transformation at a temperature well below its freezing-point, on the other hand, most definite evidences of complete recrystallisation are found. Probably the example most studied is that of iron, which undergoes at least one well-marked allotropic change at a temperature near 900° C. On passing through this temperature, either on heating or on cooling, an entirely new system of crystals is built up. Here, in the solid metal, the new crystallisation appears to arise in much the same way as in an ordinary liquid medium; minute crystals of the new phase make their appearance, and gradually spread throughout the entire mass, feeding, as they themselves grow, on the adjacent crystals of the other phase. In pure metals, where these transformations occur entirely at a single temperature, it is difficult to watch their progress. In alloys, however, the process becomes spread out over a temperature range, and the alloying element generally provides a second constituent which facilitates observation of the changes. Our knowledge of the behaviour of iron is therefore to some extent derived from, and certainly much extended by, our observations made on steels containing minute amounts of carbon. Analogous phenomena are, however, met with in other metals, notably in zinc.[1]

The scale of the crystallisation which results from the rearrangement incidental to the passage through an allotropic transformation may vary widely, but it is affected by the same causes as those which govern the size of crystals formed in a metal freezing from the liquid state. Slow cooling (or heating) tends to produce large, while rapid cooling (or heating) produces small, crystals. For this reason it is possible to utilise the operation of heating a metal through an allotropic change-point, followed by cooling through it again, as a means of refining the structure. If heating is fairly rapid, the high-temperature phase makes its appearance in the form of a very large number of minute crystals, and only if the metal is held at the high temperature for a considerable time do these crystals grow into a structure consisting of fewer and larger units. If, therefore, the metal is cooled down again at a fairly rapid rate, and after only a short sojourn at the high temperature, a redevelopment of the low-temperature phase must occur in the shape of still more numerous and smaller crystals. Provided these are not kept hot long enough to undergo growth, the resulting structure of the cold metal is very fine grained. It should be mentioned, however, that in certain very pure metals, notably electrolytic iron, there is a tendency for a very rapid formation of large crystals during the passage through the allotropic transformation,[2] and in such cases refining by the method indicated may not prove possible.

It should further be noted that it is not quite certain that the crystallisation which occurs in a solid metal is either so perfect or so complete as that which occurs during solidification from the molten state. Certain observations on the effects of strain [3] appear to indicate that the regular crystalline structure of the individual grains may not be quite so perfect in recrystallised metal as in "cast" material. There are also certain differences at and near the crystal boundaries which point in the same direction.

While recrystallisation resulting from an allotropic transformation is a relatively rare phenomenon, confined to a few metals in which well-marked allotropic changes occur, recrystallisation as an indirect result of mechanical deformation may occur in all metals and alloys which possess sufficient ductility to undergo a plastic change of shape without fracture. The process of softening a metal which has previously been hardened by working it in the cold—generally known as "annealing"—consists essentially in the application of a thermal treatment (heating) which brings about recrystallisation. It is a curious fact, however, that mechanical softening appears to occur much more rapidly than any visible change in the microstructure.

The series of phenomena associated with the recrystallisation of strained metal are very complicated, and it must be admitted that their nature and mechanism are not yet fully understood, although much research has been devoted to the matter. One of the most remarkable features of these processes is the formation, under certain conditions, of zones of large crystals—sometimes hundreds of times larger than those in adjacent regions. It has been shown fairly conclusively [4] that these large crystal formations are associated with a set of conditions in which the tendency for crystal development increases steadily from one part of the piece of metal to another. Such conditions may arise if a temperature gradient is present, while a systematic variation in the intensity of strain—a "strain gradient"—will have the same effect in a piece of metal

[1] Bingham, "The Allotropy of Zinc," *Journ. Inst. Metals*, 1920, ii.

[2] Stead and Carpenter, *Journ. Iron and Steel Inst.*, 1913, ii.

[3] Rosenhain, *Journ. Iron and Steel Inst.*, 1904, i.

[4] Jeffries, *Journ. Inst. Metals*, 1918, 2, xx.

heated uniformly. Advantage has been taken of this very vigorous crystal growth under favourable conditions to produce long wires of certain metals (zinc and tungsten) consisting of a single crystal (see also "Metals, The Relations of Strain and Structure," § (3)). The whole subject of crystal growth cannot be pursued further here; it is dealt with from other points of view in the articles already cited, and for fuller details the reader should refer to the original papers dealing with the subject.[1]

§ (5) Alloys—Solid Solution.—We have hitherto considered, mainly, the micro-structure of a pure metal; we have now to take into account the influence on that structure of one or more added elements—generally "alloying" metals—and we shall confine our attention, in the first place, to the case of a single added metal.

To begin with, the great majority of metals are completely miscible in the molten state; the few exceptions, such as lead and zinc or aluminium and antimony, may be disregarded in a general survey. We have therefore to consider what happens when a molten solution of one metal in another solidifies. Broadly speaking, two alternative courses may be followed, depending upon the nature of the metals present and upon their concentration. In one case, the metals may simply crystallise together, so that the final solid metal will ultimately be an aggregate of crystals or of crystalline grains which are all of the same chemical composition as one another and as the alloy as a whole. This can only occur if the miscibility of the two metals persists after crystallisation, and this is now generally expressed by saying that the two metals are soluble in one another in the solid state or form a "solid solution." This somewhat paradoxical term really denotes merely that, in the final crystalline condition, the two metals have preserved that condition of intimate admixture which was present in their mutual liquid solution.

Looking at the formation of these solid solutions from the atomic point of view, it would seem that, if the two metals are "soluble in the solid," the crystals can be built up out of the two kinds of atoms indiscriminately. If the two metals are "completely isomorphous" this indiscriminate building up of the two different kinds of atoms upon the same space-lattice may occur at any concentration, and the two metals will form an unbroken series of solid solutions in all their alloys. This occurs in such systems as gold-silver, copper-nickel, and several others. More frequently, however, the two kinds of atoms are not strictly interchangeable in regard to crystal building, and beyond a certain concentration the surplus atoms of one kind are formed into a separate kind of crystal. Here we have the very usual case of limited solid solubility.

Alloys of the first type, with complete mutual solid solubility, always possess the typical micro-structure of a solid solution. Those of the second type only possess this same structure within the limits of concentration covering the range of limited mutual solid solubility; beyond that range they belong to the group of "duplex" alloys.

The typical micro-structure of a solid solution, when it has attained full equilibrium, is exactly the same as that of a pure metal. The alloy consists simply of an aggregate of crystals, all having the same chemical composition. But when ordinarily cooled from fusion, such alloys rarely, if ever, attain this condition of equilibrium, and in that case they exhibit a very characteristic feature which at once allows of their identification as solid solutions as distinct from pure metals. If reference is made to the article on "Alloys, The Equilibrium Diagram," it will be seen that, with very few exceptions, the addition of a second element depresses the freezing-point of a metal, and that, further, where solid solutions are formed, the freezing process, which occurs in a pure metal at a single temperature, is spread out over a considerable range. If, now, solidification commences at a relatively high temperature and continues over a range, it is clear that the actual substance solidifying at each stage cannot have the same chemical composition. At any one point in the process, for example, it would be quite possible to separate, by mechanical means, the part which had already solidified from that which was still liquid. But this separated liquid portion could not be made to solidify except by cooling it further, so that it is in effect an alloy of lower freezing temperature, and a lower freezing temperature implies a different chemical composition.

By the aid of a properly determined equilibrium diagram it is possible to arrive at a quantitative interpretation of the whole freezing process in solid solutions. All that need be considered from the present point of view, however, is that, as a crystal of solid solution continues to grow through a range of falling temperature, its successive layers will have different chemical compositions, the inner layers or "cores" of the dendrites containing least of the dissolved metal, while the concentration of the dissolved metal increases towards the peripheries of the crystal grains. As a result, when a section of a solid solution alloy which has been cooled from fusion at any moderate rate is examined under the microscope, it is found that etching has strongly revealed the presence of these

[1] See paper by Carpenter and Elam, already cited, where full references are given.

"cores" in the dendrites. A typical example of these "cores" is shown in *Fig.* 5, which is taken from a specimen of brass containing approximately 70 per cent of copper and 30 per cent of zinc. Sometimes the composition of successive layers appears to vary rapidly, so that etching gives sharply outlined dendrites which it is at times easy to mistake for a true duplex structure. As a rule, however, the outlines are soft and blurred.

The cored dendrites, which are so often met with in cast specimens of solid-solution alloys, are not truly stable structures. If the solidification process were carried out sufficiently slowly, the chemical composition of each successive layer would become equalised with that of the previously solidified portions by the process of diffusion, and ultimately the resulting crystals would be completely homogeneous. The rate of diffusion by which such differences of composition can become equalised, however, differs widely in different alloys, but it is rarely, if ever, rapid enough to obliterate the cores during ordinary solidification. Subsequent prolonged heating, however, particularly if accompanied by mechanical working, such as forging or rolling, in many cases serves to obliterate the cores entirely. This is strikingly the case in ordinary brass, where the cored structure seen in *Fig.* 5 gives way to a homogeneous, although heavily "twinned" structure, such as that shown in *Fig.* 6.

§ (6) Duplex Alloys. — We have now to consider alloys in which the presence of a second element results in the formation of a second micro-constituent: the "duplex" alloys. According to the mode of solidification and the resulting constitution of the alloys, these second constituents take up various forms. The simplest and most frequent of these is related to the substances known as "eutectic alloys." Their mode of formation is discussed, from the thermal point of view, in the article on "Alloys, The Equilibrium Diagram." Here we need only follow the behaviour of a typical eutectiferous alloy during cooling and solidification. This process commences when the alloy cools down to the temperature of the "liquidus" curve of the equilibrium diagram — a temperature loosely spoken of as "the freezing-point" of the alloy. Here primary crystals of one metal begin to appear, and these crystals increase in size or in number or both as cooling proceeds. This separation of one of the constituent metals, however, brings with it a progressive change in the chemical composition of the residual liquid, where the concentration of the second metal continually increases. Obviously, as the temperature falls, the remaining liquid must at each stage possess the concentration necessary to keep it entirely liquid at that temperature. This process continues until a certain limit is reached. This limit exists in regard to a minimum temperature which is

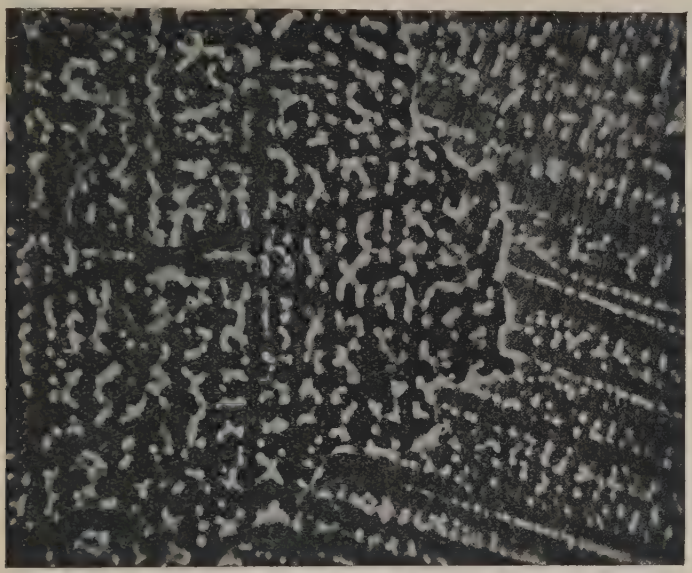

Fig. 5.—Dendritic "Cores" in Cast Brass containing 30 per cent Zinc. ×100.

the freezing temperature of the most fusible possible mixture of the two metals in question, metals, not in the form of a solid solution, but in that of closely intermingled crystals

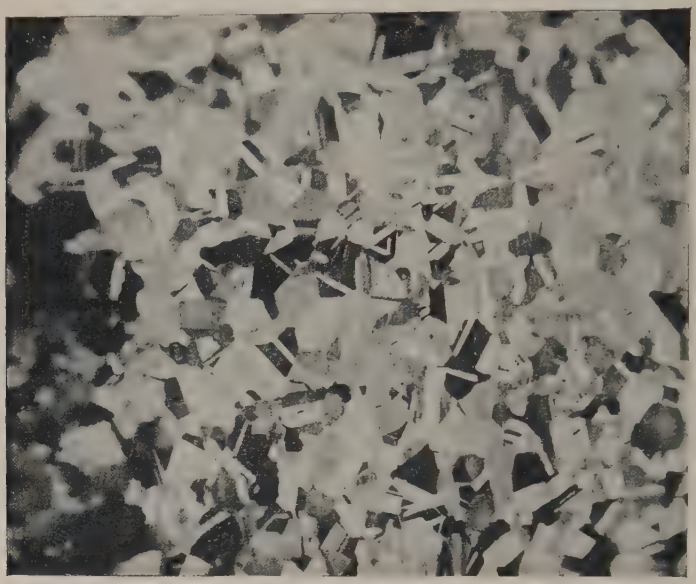

FIG. 6.—Rolled and Annealed Brass containing 30 per cent Zinc. ×100.

and this temperature and the corresponding composition of the liquid are reached simul- which frequently assume the form of parallel plates or laminae. This most fusible alloy

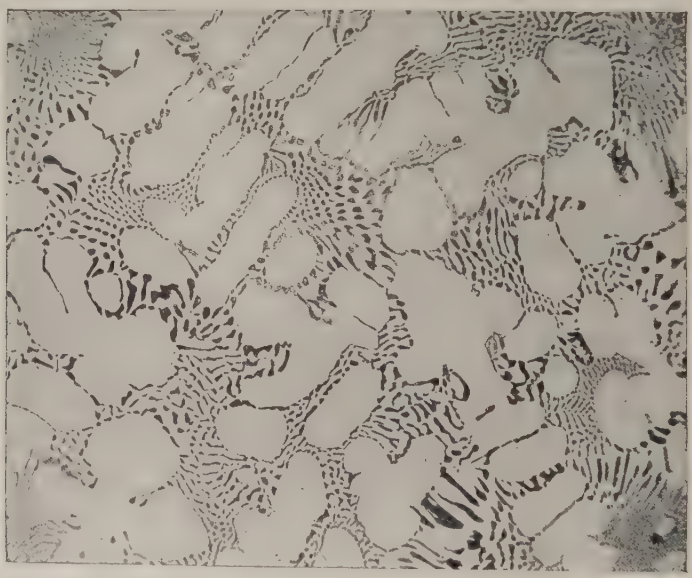

FIG. 7.—Silver-copper Alloy containing 20 per cent Copper. ×100.

taneously. Further loss of heat then results in the simultaneous solidification of both of a system is termed the "eutectic" and its microscopic appearance is often characterised

by fine laminations. Seen under very low magnifications, the regions occupied by the solidified eutectic generally appear dark, being more deeply attacked by the etching reagents. Under higher magnifications, however, the duplex character is revealed, although the laminated appearance is not a necessary or universal feature. An example of an alloy of silver and copper containing 20 per cent of copper, and showing a typical eutectic constituent, as seen under a moderate magnification (100 diameters) is shown in *Fig.* 7. A portion of a typical eutectic under a higher magnification (900 diameters) is shown in *Fig.* 8.

which has been added to the alloy does not exceed the amount capable of being retained in solid solution. When, however, eutectic does make its appearance, its amount increases proportionately to the concentration of the second metal, and the alloys with increasing concentration show increasing proportions of eutectic in their micro-structure. This is illustrated in *Figs.* 9 and 10, which represent alloys of silver and copper containing respectively 7 and 15 per cent of copper; these may be compared with *Fig.* 7, which represents an alloy of the same two metals containing 20 per cent of copper. When the alloy as a whole has the composition of the eutectic

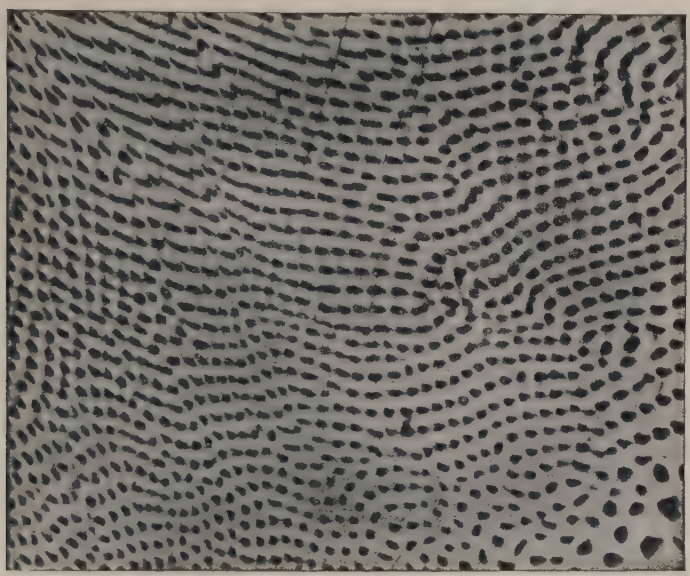

FIG. 8.—Silver-copper Eutectic Alloy. ×900.

The amount of the eutectic constituent which is seen in any given alloy will depend upon the composition of the alloy and upon the extent to which the two metals are soluble in one another in the solid state. In our sketch of the solidification of such an alloy we have for simplicity assumed that the two metals were completely immiscible in the solid state. This is never strictly true, and in the majority of cases there is a considerable degree of solid solubility. This affects the resulting structure in two ways: in the first place, the primary crystals which first appear do not consist of the pure metal but of solid solution of the second metal in the first, so that these primary crystals may exhibit a cored structure. In the second place, no eutectic at all will be present so long as the proportion of the second metal alloy, then the entire micro-section is occupied by the eutectic structure, as in *Fig.* 8.

The true nature of the structure of these duplex eutectics has received a good deal of study, and as a result the conclusion has been arrived at that they also are truly crystalline, but the crystalline orientation can only be demonstrated in one of the two constituents of the eutectic, owing to the fact that electrochemical causes make it impossible to etch the more cathodic of the two substances. It has been found, however, that in most eutectics one of the metals acts as the predominant partner and forms a kind of dendritic skeleton on which the second metal then crystallises. Most careful and delicate experiments, however, have entirely failed to show any time-lag between the crystallisation of the two metals. In many cases it is

found, further, that the orientation of the crystallisation, even in the predominant

Duplex alloys, containing a second micro-constituent, do not always contain a eutectic.

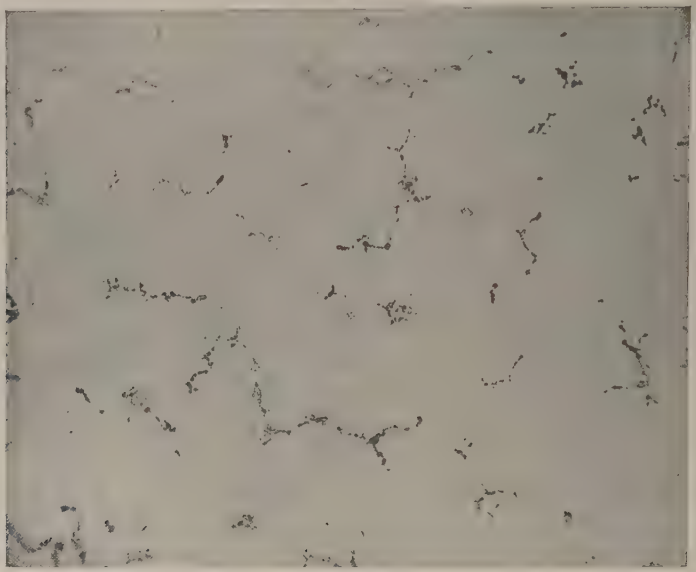

FIG. 9.—Silver-copper Alloy containing 7 per cent Copper. ×100.

metal, is radial or spherulitic rather than regular. No suggestion capable of accounting

In such cases, however, the second constituent is of the nature of an inter-metallic compound

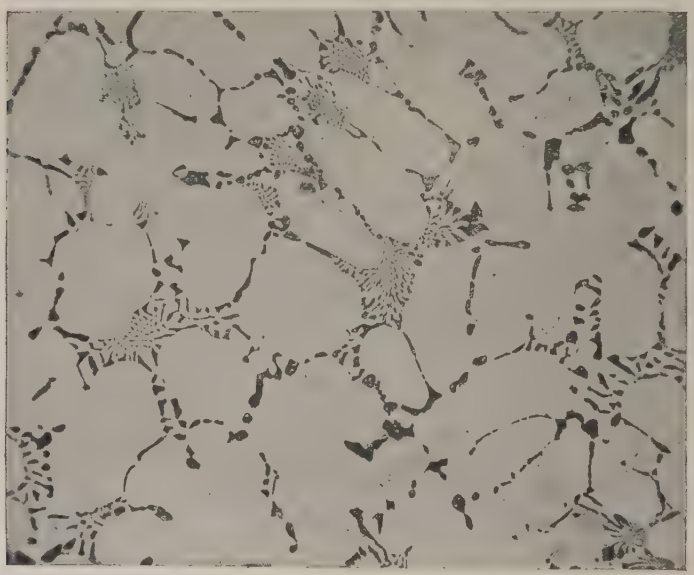

FIG. 10.—Silver-copper Alloy containing 15 per cent Copper. ×100.

for this peculiarity of eutectics has yet been put forward.

which may or may not occur in the form of a solid solution having a limited range of

existence. The alloys of copper with zinc furnish some very typical examples of this kind. An example of the micro-structure met with in such cases is shown in *Fig.* 11, which represents an alloy of copper containing 40 per cent of zinc, seen under a magnification of 150 diameters. Here the second constituent appears dark after etching, but it is strictly homogeneous and shows no signs of the typically duplex structure of a eutectic. The nature of these alloys cannot, however, be understood without detailed reference to the equilibrium diagram of the system, for which the reader is referred to the article on "Alloy Systems, Typical."

FIG. 11.—Brass containing 40 per cent of Zinc, showing Duplex Structure. ($\alpha+\beta$.) $\times 150$.

The alloys hitherto referred to are the simple binary systems containing two metals only. Where alloys containing a larger number of metals are in question, more complex structures are found. Thus the eutectic of the binary system is a duplex constituent. In ternary alloys (containing three metals) we meet not only with representatives of binary eutectics two of which may be present simultaneously, but also with a ternary eutectic which is built up of three metals which have crystallised simultaneously. In such a ternary alloy, therefore, we may find simultaneously primary crystals of one of the constituent metals, binary complexes resembling the binary eutectics but containing the third metal in solid solution, and the ternary eutectic. An example of the complex micro-structures met with in ternary alloys is given in *Fig.* 12, which represents, under a magnification of 300 diameters, an alloy containing 82·5 per cent of zinc, 10·5 per cent of aluminium, and 7 per cent of copper. The great complexity of these bodies makes it a fortunate circumstance that most alloys of practical importance are not very far removed from a binary system, further metals being generally introduced in relatively small amounts. None the less, the study of ternary and even more complex alloys is now a matter of increasing importance and is being vigorously pursued.[1]

§ (7) SOLID TRANSFORMATION.—The micro-constituents and structure so far considered are those which are formed as the result of the solidification of molten alloys. The influence of cold working (plastic deformation) and of heat treatment (annealing) on these structures is discussed elsewhere (see articles on "Metals, The Relations of Strain and Structure," and on "Metals, Thermal and Mechanical Treatment of"). Here, however, we must consider another class of micro-structures which arise from transformations which occur in certain alloys while in the solid state. The most important and interesting of these arise in connection with steel and are dealt with at length in the article on "Iron-carbon Alloys." We need only mention, therefore, that just as a liquid solution, *i.e.* a molten alloy, may on cooling deposit primary crystals of one metal, followed by a duplex eutectic, so a solid solution

[1] Rosenhain, Haughton, and Bingham, *Journ. Inst. Metals*, 1920, 1, xxiii.

may also undergo decomposition and may deposit primary crystals of one constituent, followed by a duplex constituent having a structure very similar to the typical laminated eutectic. These duplex constituents deposited from a cooling solid solution are, however, termed "eutectoids," in recognition of the analogy with and the distinction from ordinary eutectics. The most typical case is the decomposition of the solid solution of carbon in

structure is typical of a simple homogeneous solid solution. In the absence of the retarding elements named, or with slightly less rapid cooling, decomposition is not entirely prevented and, according to the rate of cooling, the microstructure shows a whole series of transition products, among which certain ones having fairly well-defined characteristics have received special names, such as Martensite, Troostite, Sorbite.

FIG. 12.—Ternary Alloy containing Zinc, 82·5 per cent; Aluminium, 10·5 per cent; Copper, 7 per cent. ×300.

hot gamma-iron and the deposition of crystals of alpha-iron (ferrite) in a matrix of eutectoid (pearlite) consisting of alternate lamellae of iron and carbide of iron. A strikingly similar eutectoid is met with in the alloys of aluminium and zinc.

In the case of iron and steel, however, there are still further complications which arise from the fact that the manner in which the decomposition of the gamma-iron solid solution takes place depends very much upon the rate of cooling. When some nickel or manganese is present, the decomposition of this solid solution can be entirely prevented by extremely rapid cooling (quenching), and the resulting micro-

For a fuller account of these special constituents of steel, and especially of hardened steel, reference must be made to the article already cited ("Iron-carbon Alloys") or to the original literature dealing with this very complex subject. Here it can only be pointed out that much of the difficulty which has arisen, and which to some extent still exists, in regard to the real nature and structure of these constituents is due to the fact that their structure is extremely minute and frequently evades the resolving power of the best modern microscope. In this field of inquiry most particularly, therefore, would an extension of the resolving power of the microscope

be welcomed. It is probable, however, that in some of these constituents we may be dealing with metal holding a second phase in something like true colloidal suspension, and in that case a very large increase in resolving power might be needed to throw real further light on the problems in question. W. R.

MICRO-STRUCTURE of binary alloys. See "Metals and Alloys, Micro-structure of," § (6).
Etched sample of commercially pure iron. See "Iron-carbon Alloys," § (2).
Of a solid solution. See "Metals and Alloys, Micro-structure of," § (7).
Of wrought iron. See "Iron-carbon Alloys," § (5).

MILD CARBON STEEL, effect of temperature on tensile strength. See "Steels, Special," § (4) (B) (i.), Table 3.

MOLTEN SOLUTION of one metal in another solidifying. See "Metals and Alloys, Micro-structure of," § (6).

MOLYBDENUM in steel. See "Steels, Special," § (33).
Physical properties of. See "Alloys, Some Special," § (4).

MONEL METAL: a nickel-copper-iron alloy, combining great strength with resistance to corrosion. See "Alloys, Some Special," § (1) (v.).

MONOVARIANT systems of alloys. See "Alloys, Constitution of," § (1) (iv.).

MONOVARIANT EQUILIBRIUM, represented by horizontal lines in an equilibrium diagram. See "Alloys, Constitution of," § (1) (v.).

MULTIPLE SYSTEM OF ARRANGING CELLS IN COPPER REFINING. See "Copper, Electrolytic Refining of," § (2).

— N —

NATURAL DRAUGHT FURNACES. See "Furnaces for Laboratory Use," § (9).

NICHROME: a trade name for an alloy consisting essentially of nickel, chromium, and iron. See "Furnaces for Laboratory Use," § (1).

NICKEL, effect of, in copper-plating bath. See "Copper, Electrolytic Refining of," § (3).
Effect of low temperatures on physical properties. See "Steels, Special," § (4) (A) (ii.).
In steel. See *ibid.* § (39).
And nickel alloys. See "Metals, Thermal and Mechanical Treatment of," § (1).

NICKEL BRASSES. See "Alloys, Some Special," § (1) (vi.).

NICKEL STEELS, non-corrodible properties. See "Steels, Special," § (48) (iii.).

NICKEL-CHROMIUM STEEL. See "Steels, Special," § (1).
Annealed; temperature, tensile strength. See *ibid.* § (4) (B) (i.), Table 3.

NITROGEN in steel. See "Steels, Special," § (26).

NON-MAGNETIC STEEL. See "Steels, Special," § (52).

NORMALISING OF STEEL: heating a steel above the critical point and cooling in air. See "Steels, Special," § (41).

NORTHRUP'S FURNACE: an electric induction furnace working at high frequencies. See "Furnaces, Electric," § (7).

— O —

OIL FURNACE. See "Furnaces for Laboratory Use," § (12).

OPAQUE HALF-FIELD REFLECTOR: a totally reflecting prism or other reflector, placed in the tube of a microscope in such a position as to cover one-half the area of the tube, as used for the examination of metals under "normal" or "vertical" illumination. See "Metals, Microscopic Examination of," § (6).

OXYGEN in steel. See "Steels, Special," § (35).

— P —

PARALLEL SYSTEM OF ARRANGING CELLS IN COPPER REFINING. See "Copper, Electrolytic Refining of," § (2)

PASS in rolled metals: the amount of reduction in thickness which is applied in a single passage through the rolls. See "Metals, Thermal and Mechanical Treatment of," § (6).

PEARLITE, a constituent of steel; appearance of, in an etched specimen. See "Iron-carbon Alloys," § (7).
Effect of rate of cooling on. See *ibid.* § (9).
Transformation into homogeneous austenite. See *ibid.* § (7).

PERMEABILITY as a physical property of steel. See "Steels, Special," § (8).

PHASE in a system of alloys. See "Alloys, Constitution of," § (1) (ii.).

Amount of, at any temperature in an equilibrium diagram. See *ibid.* § (1) (v.).

Composition of, in an equilibrium diagram. See *ibid.* § (1) (v.).

Liquid, composition of, in an equilibrium diagram. See *ibid.* § (1).

Solid, composition of, in an equilibrium diagram. See *ibid.* § (1) (v.).

PHASE RULE, application of. See "Alloys, Constitution of," § (1) (iv.); see also "Phase Rule," Vol. I.

PHOSPHOR BRONZE. See "Alloys, Some Special," § (1) (ii.).

PHOSPHORUS, existence in steel. See "Iron-carbon Alloys," § (14); also "Steels, Special," § (27).

PHOTO-ELECTRIC PROPERTIES in relation to compositions of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (11).

PHYSICAL PROPERTIES OF IRON AND STEEL, influence of temperature upon. See "Steels, Special," § (4).

PIPE: the formation of a deep central contraction cavity in ingots. See "Metals, Thermal and Mechanical Treatment of," § (2).

PIPING: the formation of a cavity in the central upper part of an ingot during solidification. See "Metals, Defects and Failure of," § (2).

PLASTIC DEFORMATION: permanent alteration of form in a metal, resulting from the application of stress in excess of the limit of elastic recovery. See "Metals, The Relations of Strain and Structure," § (1).

PLOTTING CHRONOGRAPH. See "Metals, Thermal Study of," § (6).

POLISH ATTACK: a method of preparing metal micro-sections by a polishing process carried on in the presence of a slightly corrosive liquid unable by itself to produce satisfactory etching. See "Metals, Microscopic Examination of," § (2) (iv.).

POLISHING, BEILBY'S THEORY OF. See "Solids, The Flow of."

PORCELAIN, composition of. See "Refractories," § (39).

Properties of. See *ibid.* § (41).

POTENTIOMETER, use for measurement of thermal E.M.F. See "Metals, Thermal Study of," § (4).

POWDER, VITREOUS NATURE OF A FINE, due to the extent to which the transformation from the crystalline state has been affected by flow during grinding. See "Solids, The Flow of."

PURE IRON. Specific gravity 7·892. See "Steels, Special," § (5); see also "Iron-carbon Alloys," § (1).

— Q —

QUATERNARY ALLOYS: systems of alloys containing four component metals. See "Steels, Special," § (11) (ii.); also "Alloys, Constitution of," § (6).

— R —

RADIATION FURNACES. See "Indirect Arc Furnace"; see also "Furnaces, Electric," § (4) (vii.).

RAILWAY STEELS: generally carbon steels of 0·2-0·7 per cent carbon. Analysis; mechanical properties. See "Steels, Special," § (46) (ii.), Table 10.

RARE EARTHS as alloys with light metals. See "Alloys, Some Special," § (5).

REAGENTS, ACID, for etching metals and alloys. See "Metals, Microscopic Examination of," § (2) (i.).

RECRYSTALLISATION of strained metal. See "Metals and Alloys, Micro-structure of," § (5).

RECRYSTALLISATION IN METALS, where allotropic transformation takes place below their freezing-point. See "Metals and Alloys, Micro-structure of," § (5).

RECUPERATIVE FURNACE. A recuperative furnace working on natural draught has been designed by Seger for testing refractory materials. Another larger furnace has been designed at the National Physical Laboratory for firing and testing refractory materials and for experimental glass-melting. See "Furnaces for Laboratory Use," § (9).

REFRACTORIES, summary of properties of. See "Refractories," § (55).

REFRACTORIES [1]

I. Introductory

§ (1) The term "refractories" denotes materials which are available for use in operations which require to be carried out at high temperatures.

The term refractoriness is generally applied only to the thermal properties of a material, *i.e.* its resistance to high temperature, although occasionally we find a body highly resistant to corrosion designated as refractory.

In the category of refractories are grouped certain heat-resisting alloys, metallic cements, some silicates (such as clay which may be regarded as an aluminium silicate), and a number of oxides, nitrides, carbides, etc.

Refractories are employed in the construction of furnaces, muffles, crucibles, ladles, stirring rods, and so on. For service in the lower high-temperature range (not over 1000° C.) metallic alloys are sometimes used for the manufacture of muffles and crucibles, and for extremely high temperatures (over, say, 1650° C.) oxides (*e.g.* magnesium oxide) and such bodies as carborundum (silicon carbide), and, in the laboratory, metallic platinum and iridium and the rarer oxides, such as zirconia. A large majority of refractories, however, covering a working temperature range of from, say, 1000° to 1700° C., consist of silica—either combined with alumina in the form of fireclay (the Al_2O_3 varying from 10 to 40 per cent) or as a siliceous refractory containing over 90 per cent of SiO_2.

In general, refractory materials only acquire satisfactory mechanical properties after they have been exposed to a high temperature for some time. For example, fireclays as they are mined are friable and disintegrate under the action of water; it requires a temperature exceeding about 1200° C. to impart to the material the characteristic properties of a firebrick. Similarly, a silica brick is fragile and of little use as a refractory until it has been fired to a temperature exceeding 1400° C. An adequate initial heating (in some cases to a temperature exceeding the subsequent working temperature) is essential to ensure stability in use.

A refractory material must be not only reasonably stable at high temperatures, but must possess certain chemical and physical properties which render it suitable for the purpose for which it is employed.

To frame a specification for a refractory material for any particular purpose we must know, therefore, first, the chemical, physical, or mechanical conditions under which it is to be used, and, secondly, the temperature or range of temperatures at which these conditions prevail.

It is, accordingly, difficult to formulate a rational classification of refractories, since any classification based solely on chemical grounds will be of little use from a physical standpoint and is not by any means the only criterion of the value of the material, even with respect to its softening-point at high temperatures.

The value of a refractory article thus depends on a combination of properties, and we seldom find that a material selected for a special purpose is the best which could be obtained for any operation other than that for which it was originally selected. Thus the failure of a refractory in service often arises from the injudicious selection of materials and from the application to one process of a material best suited to another. Frequently a refractory is required to withstand treatment which calls for properties only obtainable at the sacrifice of other properties equally indispensable, and we have then to effect a compromise. For example, it is often desired to obtain refractories which must (*a*) resist the corrosion of a fluxing agent, and (*b*) withstand rapid fluctuations in temperature during the operation. To obtain the maximum resistance to corrosion it is necessary to use a dense non-porous body, whereas to resist a sudden change of temperature without cracking an open, porous, lightly fired body is the most suitable. For this purpose, therefore, it is necessary to make use of a refractory of medium porosity which will give a reasonable life as regards both (*a*) and (*b*), but which could easily be surpassed if only one aspect, either (*a*) or (*b*), had to be considered.

As a rule the process of manufacture and, consequently, the physical and mechanical properties are of greater importance than the ultimate chemical composition of the material, since, at high temperatures, we are dealing generally with arrested reactions, few refractories being in a condition of stable equilibrium, and the rates of reaction between the constituents are governed largely by the texture and certain other properties, notably the viscosity, of the body.

§ (2) Softening-point.—Generally speaking, a refractory consists of particles of highly infusible material, which may be either amorphous or crystalline, cemented together with a more fusible, amorphous bond.

For example, a silica brick containing, say, 94 per cent of silica will consist of a refractory skeleton of more or less pure crystalline silica (quartz, tridymite, or cristobalite) cemented together with a glass composed of impurities in the original silica together with fluxes (usually lime) added to increase the amount of bonding material. In this case the amorphous

[1] The Arabic numerals in the text, thus (1), refer to the classified list of references at the end of the section.

material will consist of, roughly, CaO 20 per cent, Al_2O_3 10 per cent, Fe_2O_3 10 per cent, the balance being silica.

At high temperatures this bonding substance becomes fluid and a process of solution begins, the infusible constituent dissolving slowly in the liquid, which thereby becomes more refractory. Hence the viscosity of the bond increases with the time the refractory is maintained at any particular temperature, and at the same time the quantity of the liquid phase increases at the expense of the solid, infusible constituents.

As the quantity of liquid phase increases the refractory as a whole shows a readiness to undergo plastic deformation. This plasticity persists over a considerable range of concentration of the solid phase in the liquid (the actual range depending chiefly on the size of the solid particles), and finally, when a sufficient quantity of the solid has dissolved, viscous flow takes place and the refractory as a whole assumes a viscosity which is a function of that of the liquid phase.

A refractory body cannot therefore be said to possess a melting-point in a strict sense, but begins to flow when the concentration of solid phase reaches a certain minimum, and is capable of deformation under load at lower temperatures which depend on the pressure and on the ratio of solid to liquid phases.

It is clear, therefore, that, since the mechanical behaviour of the refractory at high temperature depends on this ratio and on the properties, notably the viscosity, of the liquid, the conditions which control these determine largely the behaviour of the refractory. Hence, we have to consider the temperature coefficient of viscosity of the bonding material and the solubility and rate of solution of the infusible constituents in it, this latter factor being dependent on the fineness of texture of the refractory, and together with these the influence of the dissolved material on the viscosity of the fusible matrix.

In practice the problem is more complex, since we frequently find that new phases crystallise out of the fusible solution and, in addition, that the infusible constituents undergo transformations to allotropic modifications. The process of solution and recrystallisation gives rise to changes in density and porosity, and the consequent shrinkages and expansions are accompanied by changes in the mechanical properties of the refractory.

The ratio of liquid to solid is controlled largely by the time and temperature at which the body has been fired, and it might perhaps be thought that since a prolonged firing increases the quantity of liquid phase an underfired body was desirable. This is, however, not generally the case, since the advantages which follow from a liquid phase of high viscosity, combined with the phases which crystallise out of the solution, outweigh the detrimental effect which an excess of liquid phase might be expected to produce.

§ (3) Measurement of Softening-point.—Many suggestions have been put forward with a view to standardising the measurement of the softening-points of refractories. The problem presents some difficulties, since it is necessary to define three variables, time, temperature, and pressure, and a careful control over these is required during the determination of the softening-point, since the properties of the refractory are changing rapidly at temperatures in the neighbourhood of the softening-point.

A convenient criterion of the softening-point, and that usually adopted, is to make a small tetrahedral cone—about 2 inches high—of the refractory and to subject it to a temperature rising at a known steady rate (that usually adopted is 10° C. per minute), the softening temperature being that at which the cone bends under gravity and the tip just touches the floor on which the cone stands. This procedure is, of course, purely arbitrary and has no obvious physical meaning, but, in practice, it gives satisfactory comparative results. Since the rate of rise of temperature is difficult to control and results obtained at different rates are hard to co-ordinate, it has been found convenient to compare refractories with standard cones, made up from silicate mixtures, of similar dimensions, heated together with the refractory under test. By this means the effect of variations in the rate of heating are minimised. This system has the further advantage of avoiding the necessity of direct measurement of the temperature during the test, a performance which is liable to serious error except in the hands of skilled operators with refined apparatus. A set of cones was devised by Seger, and these have been generally adopted as standards of reference.

On opposite page is given a list of Seger cones,[1] together with their compositions and the temperatures corresponding roughly to their softening-points (or "squatting temperatures" as they are usually called), with a rate of heating of approximately 10° C. per minute.

A variation in the rate of heating may make a difference of anything up to 100° C. in the squatting temperature. The higher the rate the higher the squatting temperature. There are, unfortunately, other standards in use, and although some are in some respects more satisfactory than the Seger cones, the confusion which arises through the multiplication of standards more than outweighs the advantages of their use.

[1] "Physical Chemistry of Seger Cones," Sosman, *Trans. Amer. Cer. Soc.* xv. 482.

List of Cones

Cone No.	Chemical Composition.	Temperature of Softening °C.
010 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·50 SiO_2 0·45 B_2O_3	900
09 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·55 SiO_2 0·50 B_2O_3	920
08 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·60 SiO_2 0·40 B_2O_3	940
07 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·65 SiO_2 0·35 B_2O_3	960
06 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·70 SiO_2 0·30 B_2O_3	980
05 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·75 SiO_2 0·25 B_2O_3	1000
04 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·80 SiO_2 0·20 B_2O_3	1020
03 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·85 SiO_2 0·15 B_2O_3	1040
02 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·90 SiO_2 0·10 B_2O_3	1060
01 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 3·95 SiO_2 0·05 B_2O_3	1080
1 . .	0·3 K_2O 0·7 CaO . . 0·2 Fe_2O_3 . . 0·3 Al_2O_3 . . 4 SiO_2	1100
2 . .	0·3 K_2O 0·7 CaO . . 0·1 Fe_2O_3 . . 0·4 Al_2O_3 . . 4 SiO_2	1120
3 . .	0·3 K_2O 0·7 CaO . . 0·05 Fe_2O_3 . . 0·45 Al_2O_3 . . 4 SiO_2	1140
4 . .	0·3 K_2O 0·7 CaO . . 0·5 Al_2O_3 . . 4 SiO_2	1160
5 . .	0·3 K_2O 0·7 CaO . . 0·5 Al_2O_3 . . 5 SiO_2	1180
6 . .	0·3 K_2O 0·7 CaO . . 0·6 Al_2O_3 . . 6 SiO_2	1200
7 . .	0·3 K_2O 0·7 CaO . . 0·7 Al_2O_3 . . 7 SiO_2	1230
8 . .	0·3 K_2O 0·7 CaO . . 0·8 Al_2O_3 . . 8 SiO_2	1250
9 . .	0·3 K_2O 0·7 CaO . . 0·9 Al_2O_3 . . 9 SiO_2	1280
10 . .	0·3 K_2O 0·7 CaO . . 1·0 Al_2O_3 . . 10 SiO_2	1300
11 . .	0·3 K_2O 0·7 CaO . . 1·2 Al_2O_3 . . 12 SiO_2	1320
12 . .	0·3 K_2O 0·7 CaO . . 1·4 Al_2O_3 . . 14 SiO_2	1350
13 . .	0·3 K_2O 0·7 CaO . . 1·6 Al_2O_3 . . 16 SiO_2	1380
14 . .	0·3 K_2O 0·7 CaO . . 1·8 Al_2O_3 . . 18 SiO_2	1410
15 . .	0·3 K_2O 0·7 CaO . . 2·1 Al_2O_3 . . 21 SiO_2	1435
16 . .	0·3 K_2O 0·7 CaO . . 2·4 Al_2O_3 . . 24 SiO_2	1460
17 . .	0·3 K_2O 0·7 CaO . . 2·7 Al_2O_3 . . 27 SiO_2	1480
18 . .	0·3 K_2O 0·7 CaO . . 3·1 Al_2O_3 . . 31 SiO_2	1500
19 . .	0·3 K_2O 0·7 CaO . . 3·5 Al_2O_3 . . 35 SiO_2	1520
20 . .	0·3 K_2O 0·7 CaO . . 3·9 Al_2O_3 . . 39 SiO_2	1530
26 . .	0·3 K_2O 0·7 CaO . . 7·2 Al_2O_3 . . 72 SiO_2	1580
27 . .	0·3 K_2O 0·7 CaO . . 20 Al_2O_3 . 200 SiO_2	1610
28 . .	.. . . Al_2O_3 . . 10 SiO_2	1630
29 . .	.. . . Al_2O_3 . . 8 SiO_2	1650
30 . .	.. . . Al_2O_3 . . 6 SiO_2	1670
31 . .	.. . . Al_2O_3 . . 5 SiO_2	1690
32 . .	.. . . Al_2O_3 . . 4 SiO_2	1710
33 . .	.. . . Al_2O_3 . . 3 SiO_2	1730
34 . .	.. . . Al_2O_3 . . 2·5 SiO_2	1750
35 . .	.. . . Al_2O_3 . . 2 SiO_2	1770
36 . .	.. . . Al_2O_3 . . 2 SiO_2	1790
37 . .	.. . . Al_2O_3 . . 1·66 SiO_2	1825
38 . .	.. . . Al_2O_3 . . 1·33 SiO_2	1850
39 . .	.. . . Al_2O_3 . . 1 SiO_2	1860
40 . .	.. . . Al_2O_3 . . 0·66 SiO_2	1920
41 . .	.. . . Al_2O_3 . . 0·33 SiO_2	1960
42 . .	.. . . . . Al_2O_3	2000

Heraeus pressed an iridium rod, 9 mm. diameter, into the refractory and determined the temperature at which (i.) the rod began to penetrate and (ii.) the rod sank into the refractory at the rate of 1 mm. per minute. He used a high pressure, 400 gm. per sq. mm., and found that the penetration began from 250°-300° C. below the softening-point, but that the temperature at which the standard rate of penetration was obtained varied very considerably with different clays and bore no apparent relation to the softening-point.[1] Bleininger and Brown[2] carried out tests on clay at temperatures of 1300° and 1350° under loads of 75 and 50 lbs. per sq. in.

§ (4) Classification.—We can conveniently divide refractories into a number of groups, as under:

(*a*) Refractories of which the principal constituent is clay.
(*b*) Siliceous refractories.
(*c*) Porcelain.
(*d*) Carbonaceous refractories.
(*e*) Refractory oxides, carbides, etc.

II. Refractory Clays

§ (5) General Properties of Clays.—Clay is the fundamental base of a large class of refractories. The term clay is used to describe a mixture of minerals, the principal constituents being mica, felspar, quartz, and hydrated aluminium silicates corresponding closely to the formula $(Al_2O_3\ 2SiO_2\ 2H_2O)_n$. This latter constituent, which Mellor has called clayite, is an exceedingly fine-grained material, being composed of particles ranging in size from about 2 μ downwards, and exhibiting strongly the Brownian movement. Clayite is decomposed by sulphuric acid, whereas quartz, felspar, mica, etc., are not. Advantage is taken of this fact in the so-called "rational analysis" of clays. By this method the clayite—or clay substance—is decomposed and taken into solution by H_2SO_4 and the residue is regarded as felspar and quartz. The aluminium in this residue is then determined and the felspar calculated on this basis, the quartz being estimated by difference. The results obtained by this method (with certain refinements) are not very satisfactory and only approximate to the composition of the clay. A more satisfactory estimate of the mineralogical composition can be calculated from the complete analysis, assuming the sodium and potassium to be present as albite ($Na_2O\ Al_2O_3\ 6SiO_2$) and orthoclase ($K_2O\ Al_2O_3\ 6SiO_2$), the calcium as anorthite ($CaO\ Al_2O_3\ 2SiO_2$). (Rather more satisfactory results are obtained if the potash is reckoned as muscovite, according to the formula $K_2O\ 3Al_2O_3\ 6SiO_2\ 2H_2O$.). The remaining alumina enables the clayite to be calculated, and the surplus silica is reckoned as quartz.

Analyses of typical clays are given in § (19).

Most clays contain a considerable quantity of free silica and a few bauxitic clays contain free alumina. For the effect of different constituents on the properties of clays see § (19).

Clays may be divided into two classes, residual and sedimentary. The residual clays are the residue from the decomposition of rocks, chiefly felspathic, through the agency of water and carbonic acid, the alkaline silicates, etc., being washed away. The sedimentary clay deposits are formed by the transportation of the residual clay by water and are usually of finer grain than the residual clays. The most useful refractory clays are:

(i.) Kaolin or China clay, a residual clay generally contaminated with mica and quartz, from which it is separated by washing. Kaolin (which should not be confused with the mineral kaolinite) approximates closely in composition to clayite ($Al_2O_3\ 2SiO_2\ 2H_2O$).

(ii.) Ball clays, sedimentary highly plastic clays, frequently containing high percentages of soluble salts and organic matter. Good ball clay is used as a bond for more refractory clays.

(iii.) Fireclays, a term generally applied to residual clays associated with the coal measures. These clays vary very considerably in composition, grain, size, and properties; they are more fully described below.

§ (6) Plasticity.—The property most characteristic of clays is that of developing plasticity when wet. The degree of plasticity varies greatly in different clays. We may tentatively define a plastic body as one which undergoes permanent deformation without rupture under a finite shearing stress which has a lower limiting value. We can distinguish between a plastic and a viscous body, since the latter undergoes deformation under a load which has no lower limiting value. We have thus several distinct factors which make up the property of plasticity. It depends on the friction which determines the stress required to produce deformation and the mobility of the body when this friction is overcome.

No successful attempts have been made to classify clays by a direct determination of the mechanical property of plasticity as obtained by the measurement of the deformation the clay will stand without rupture, or the mobility of the clay under stress just sufficient to overcome friction. With most clays, when at the consistency best suited for working, the stress is of the order of 50 lbs. per square inch.

One common but misleading use of the term plasticity precludes the possibility of defining

[1] Heraeus, *Zeit. f. angew. Chem.* 18 (1905), 49.
[2] Bleininger and Brown, *Technologic Paper of Bureau of Standards*, No. 7.

it rationally in terms of mobility and limiting stress, since the word is used to denote the range of concentration over which the clay has plastic properties, *i.e.* the difference between the concentration of solid at the point where friction is zero and at the point where the mobility approaches zero and the friction is high (the concentration of solid at this latter point approximates to the closest possible packing of solid particles and is therefore independent of the size of particle).

The finer the particles of the clay, the longer will be the range of concentration over which the clay is plastic and the greater the mobility at the concentration of solid at which plastic flow ceases and viscous flow begins.

From the above considerations a number of indirect methods have been developed to evaluate the comparative plasticity of clays. Probably no method is so sensitive as the feel of the clay to the hand of the skilled worker. A quantitative basis is, however, desirable for comparative purposes. Still it is obvious that none of the methods for assigning an index for plasticity which are outlined below, indicate the true physical conception of plasticity; they rather give a value roughly proportional to the plasticity.

The simplest criterion of plasticity is the determination of the "water of plasticity." The clay is moistened and kneaded to the best consistency for working, and the moisture content is determined and tabulated as the "water of plasticity." This test gives the concentration of solid particles when the clay is in its best working condition. The higher the water of plasticity the more plastic the clay. It sometimes happens, however, that two clays may have similar waters of plasticity while yet the ranges over which they remain plastic are widely different. A further test is therefore required. In this connection, a test devised by Atterberg is useful. The clay is placed on a flat disc and moistened to such a consistency that a slot of \/-shaped section cut across the clay slab (which should be about $\frac{1}{4}$ in. thick) will just close up to a V section on the disc being tapped. The water content of the clay is then determined. The clay is then dried until it is just too "short" to roll into a rod on the palm of the hand without crumbling. The water content of the clay is again determined and the difference between this and the former value (reckoned as percentage water in the clay) is known as the Atterberg plasticity number. This number, taken in conjunction with the water of plasticity, gives a good evaluation of the plasticity of a clay.

It is generally believed that the particles of clayite are coated with a thin film of colloidal substance, which consists partly of organic colloids and partly of colloidal silicates, silicic acid, and hydroxides of aluminium, iron, etc. The amount of the colloids present is a function of the size of the clay particle and therefore of the plasticity, and an estimate of the colloids in the clay is found to agree with other methods of gauging the plasticity. The percentage of colloid can be conveniently estimated colorimetrically with a standard dye solution (malachite green is suitable for the purpose). For maximum plasticity the amount of colloidal substance should lie between 0·5 per cent and 1·5 per cent. Below 0·5 per cent the clay is too "short" and above 1·5 per cent too sticky for comfortable working.[1]

Plasticity may also be evaluated comparatively by means of the drying shrinkage and tensile strength of the dried clay. In the latter case the clay is sometimes mixed with sand, since with a highly plastic clay it is found impossible to dry test pieces without the formation of small cracks which give a low value to the tensile strength. A mixture of clay and sand can be dried without fear of cracking.

Another indirect method of estimating plasticity is a slaking test. A sample of a clay is moulded to a cube and dried. It is then placed in water and the time taken for the clay to break down is determined. A strong plastic clay will resist the slaking action of the water for some hours, whereas a kaolin will disintegrate in a few minutes.

The above tests can all be used to estimate the value of a clay for bonding purposes.

The rate of drying is an important factor in the behaviour of clay. This can be determined by measuring the linear shrinkage and determining the time taken for complete shrinkage to occur. With slow-drying clays it is difficult to avoid serious cracks during drying, and incomplete drying before the ware is fired is a cause of much trouble to users and manufacturers of refractories.

§ (7) Deflocculation.—The properties of clays are profoundly modified by the addition of an electrolyte. The viscosity of clay "slips" (a term used to denote a clay mixture when diluted with water to form a liquid) can be controlled by the addition of suitable reagents; the plasticity of a clay is affected in a similar manner. The general behaviour of clays towards reagents is determined by the solubility relations of the possible solid phases. We have, in a clay, colloidal silicates, silicic acid, hydroxides of aluminium, iron, etc., salts of lime and the alkalis and, often, organic matter. Any reaction which tends to increase the size of the particles of the disperse phases, converting sols into gels, causes an increase in the plasticity of the clay. (The phenomenon

[1] "Technical Control of the Colloidal Matter of Clays," H. E. Ashley, *Tech. Paper of Bureau of Standards*, No. 23.

is usually known as flocculation, the converse being termed deflocculation.)

The flocculating or deflocculating action is chiefly due (i.) to changes in the solubility of the participating phases; this may be brought about by exchanges of bases, the precipitation of insoluble compounds or a "salting out" action, or (ii.) to changes in the electrical charges on the particles in suspension. Reagents which exert a flocculating action in clays are acids, acid salts, lime, calcium sulphate, sodium chloride, and most neutral salts. The principal deflocculators are ammonia, alkali hydroxides or carbonates, borates, silicates, and salts of the weaker acids.

These deflocculating agents have, in general, a certain concentration at which the maximum degree of deflocculation exists; excess of the reagent decreases the degree of deflocculation. Thus, with sodium carbonate—Na_2CO_3—the relation between viscosity and concentration of the Na_2CO_3 in a slip is as follows: [1]

Time taken for Slip to flow through an Orifice.	Grams of Na_2CO_3 added to 110 grm. of Water and 68 grm. Clay Body.
Secs.	
11½	0
10	0·1
8½	0·2
7½	0·3
7	0·4
7	0·5
7½	1·0
7½	1·5
9	2·5
16	3·5

To increase the fluidity of clay slips used in the casting process (see § (11)) a common practice is to use a mixture of sodium carbonate and sodium silicate as a deflocculant. The mixture has certain advantages over either one of these reagents.

§ (8) The Action of Heat on Clay.—When clay is heated certain well-marked changes occur in its constitution. On heating to above 100° C. the absorbed moisture and water held in the pores is driven off. On further heating an endothermic reaction is observed in the neighbourhood of 500° C. At this point a marked change in the properties of the clay takes place. Up to this point the plasticity, which has been destroyed by heating, can be restored by prolonged treatment with water; after the endothermic reaction has occurred the plasticity can no longer wholly be restored. The temperature at which clays permanently lose their plasticity varies. The plasticity of surface clays cannot be restored after heating to about 400° C., in a ball clay it is generally lost at 450° C., in china clay at about 500° C. Some shales appear to improve in plasticity on heating to this temperature, and a temperature considerably higher is required to destroy their plasticity. In the neighbourhood of the endothermic range the combined water is driven off, and the clay becomes partly soluble in HCl. There is a considerable range of temperature throughout which the combined water can be expelled by prolonged heating.

Mellor suggests that the clay, at this point, breaks down, forming free silica and alumina. Other suggestions have been put forward, *e.g.* the formation of compounds such as $Al_2O_3\ SiO_2$ and $Al_2O_3\ 3SiO_2$, etc. If silica be liberated it is an amorphous form, since no trace of the inversions of α-β quartz occurring at 575° or tridymite at 117° C., etc. (see § (30)), can be detected.

On further heating no change occurs until, in the neighbourhood of 800°-950° C., there is an exothermic reaction. According to Mellor, this reaction denotes the polymerisation of the alumina, which, on heating the clay to this point, becomes insoluble in HCl.

The specific gravity of clays falls on heating, until the exothermic reaction occurs, at which point it reaches a minimum. This minimum is sharply defined in the case of pure clays, but not in the more impure clays, which also lose their combined water over a longer range than do the purer varieties. Above this point the specific gravity slowly rises with rising temperature.

As the clay is heated to still higher temperatures further changes take place. In the absence of an appreciable amount of fluxing material amorphous sillimanite ($Al_2O_3\ SiO_2$) appears to be formed at about 1200° C. A high-grade kaolin (china clay) will show faint traces of the separation of an isotropic material of refractive index differing from that of the matrix, which is also amorphous.

At 1400° C., and more rapidly at higher temperatures, needle-shaped crystals of sillimanite appear in this isotropic material, suggesting that amorphous sillimanite is formed by the interaction of the products of the decomposition of the clayite molecule at a point where the viscosity is too high to permit of molecular orientation in a short time.

Most clays, however, contain appreciable quantities of felspathic material, together with traces of compounds of iron, calcium, magnesium, etc., with the result that eutectics, having melting-points well below 1200°, are usually formed and the clayite dissolves in the liquid phase, giving rise, in aluminous clays, to a precipitation of crystals of sillimanite. As indicated in § (2) the solution of silica and alumina in the fused material raises its viscosity until, if the temperature be maintained

[1] Taken from Mellor, *Trans. Cer. Soc.*, 1908, vi. 161.

constant, a point is reached where the rate of solution becomes negligibly small.

The presence of a liquid phase in appreciable quantities causes a large contraction in the clay body, under the action of surface tension. Thus, on firing dried clay articles, we find first an expansion in size at about 500° C. followed by a slight contraction up to about 1000° C., a contraction often less than the previous expansion, with the result that lightly fired clay articles (fired to say 1000° C.) may be actually larger than the original article after drying.

§ (9) Porosity.—From this point, as the temperature of firing rises, there is a rapid shrinkage, as the presence of the fluxes becomes apparent, and the porosity falls from the neighbourhood of 40 until the clay is completely vitrified, with zero porosity. (The porosity is usually reckoned as the ratio of the volume of the pore spaces in the body to the total volume.) Actually, a porosity of zero is rarely found, since on vitrification a number of air bubbles are trapped in the viscous material, giving at least 2 or 3 per cent of closed pores. It is customary to differentiate between true and apparent porosity, the latter being the porosity calculated on the open pores, *i.e.* the pores accessible to a liquid if the body be heated in the liquid under reduced pressure. The true porosity can be determined by the estimation of the density of the finely powdered material and subsequent calculation from the weight of a known volume of the material. The apparent porosity is determined by weighing the body (i.) dry, (ii.) saturated with a liquid of known specific gravity, usually water or xylene (by boiling under reduced pressure), and finally (iii.) weighing suspended in the liquid. The porosity P is given by the equation

$$P = \frac{\text{Weight wet} - \text{Weight dry}}{\text{Weight wet} - \text{Weight in water}}.$$

With refractories having an apparent porosity of 15 per cent upwards the closed pores are few and may be neglected, but with an apparent porosity of less than 10 per cent the closed pores become appreciable, frequently with dense bodies amounting to 4 or 6 per cent.

The large shrinkage which occurs on firing clay refractories is due almost entirely to the closing of the pores. On vitrification or "sintering" there is an actual expansion of the clay (*i.e.* a drop in true specific gravity), which, however, is masked by the shrinkage owing to the decrease in porosity.

§ (10) Grog.—In the manufacture of refractory articles, this rapid shrinkage would invariably give rise to cracks when the body was fired and, accordingly, the shrinkage is reduced by the addition to the clay of some inert material which undergoes little shrinkage during the firing. This generally takes the form of previously burnt clay which is ground and mixed with the raw clay, although special materials, such as carborundum (SiC) are sometimes used. The addition of this inert material, technically known as grog, produces certain changes in the properties of the body.

For any particular size of article, there exists a maximum size in grog if satisfactory physical properties are expected. For most practical purposes it is generally desirable to approach as closely as possible to that limit.

The grading of the grog exercises a considerable influence on the properties of the refractory. Generally speaking, the grog should be graded in such a way that the larger particles should form a skeleton throughout the body and that the smaller particles should be graded to fill the voids between the larger.

The effect of suitable grading chiefly shows itself in the properties of the clay body in the unburnt condition and when fired to temperatures below the vitrification point of the clay.

When the clay begins to vitrify, other factors predominate in determining the strength of the clay body, *e.g.* the fluxes and the surface factor of the grog. The surface factor is determined by the area of surface per unit weight.[1]

The higher the surface factor of the grog, the stronger the refractory and the less resistant to sudden changes of temperature. The higher the total percentage of grog present, the less likely is the refractory to crack with a rapid change of temperature, but the weaker is the mechanical strength.

There is an appreciable difference in the properties of the refractory according as porous grog is moistened before mixing with the clay or is mixed dry with the clay. In the former case a more open structure is produced and the refractory is more resistant to a rapid change of temperature.

Since the presence of grog increases the porosity of the refractory, we frequently find that a high percentage of grog increases the refractoriness because the fluxes are not in such intimate contact with the refractory skeleton of the block. The fluxes in the grog, which is, or should be, fired to a temperature exceeding that to which the refractory is fired or at which it is to be used, are rich in dissolved SiO_2 and Al_2O_3, and the grog as a whole is less likely to squat under load than the bonding clay.

§ (11) The Manufacture of Fireclay Articles.—Three processes are in general use for the manufacture of refractory articles: (i.) moulding, (ii.) pressing, (iii.) casting.

(i.) *Moulding.*—In this process advantage is taken of the plasticity of the clay, which is

[1] Purdy, *Trans. Amer. Cer. Soc.*, 1905, vii. 441; Mellor, *Trans. Eng. Cer. Soc.*, 1910, ix. 94.

moistened to the desired consistency, to develop maximum plasticity, and moulded into the required shape with or without the aid of a mould.

The clay, after mining, is carefully picked by skilled sorters who endeavour to remove all iron nodules and any gross impurities. The importance of careful picking in the manufacture of the best fireclay articles cannot be over-estimated. Frequently, clay from good seams is partially spoiled by lack of due attention to the picking. The selected clay is then "weathered," that is, laid aside in the open, exposed to the action of frost, rain, and air for some time—months, or in some cases years.

The changes which take place during the weathering process vary considerably in degree with different types of clay. Some clays are comparatively unaffected, but, in general, the properties are to a great extent modified. The structure of the clay is broken down and it is rendered friable. The plasticity is greatly increased, soluble salts partially removed, and a marked increase observed in the colloidal content of the clay. (A few instances are found where properties of the clay are affected adversely by weathering.)

The clay is generally spread out in beds to weather, and is often sprayed periodically with water. Some manufacturers subject their clays to treatment with steam to improve their plasticity.

The clay, after weathering, is usually first crushed in some form of jaw crusher and then ground in an edge runner mill. This mill consists of a steel pan, a part of the bottom of which is perforated to allow the ground clay to pass. The grinding is effected by two massive iron discs (sometimes fitted with steel tyres) which are free to revolve on edge about a common horizontal axis.

There are two types of edge runner in use; in one the axle bearing the discs is revolved about the middle point, the discs running in a fixed pan, and in the other the axle of the discs is fixed and the pan is revolved.

The clay is sometimes ground in ball mills instead of edge runner mills. The type commonly used consists of a steel revolving drum, lined with flint and charged with flint pebbles.

After grinding, the clay is screened, any coarse particles being retained for further grinding. The grading of the clay in some cases is important, particularly if, for some special purpose, little or no grog is being used.

In some works the practice of mixing all or a part of the grog with the clay before grinding is adopted, and the clay and grog are ground together. This practice has some advantages, inasmuch as a thorough incorporation of the grog in the clay is secured, but it has the disadvantages that it is somewhat difficult to control adequately the grading of the grog and that it entails the mixing of the clay with the dry grog, an undesirable procedure if an open structure is desired. The total percentage of grog which can be used conveniently depends largely on the binding power of the clay. If too high a grog content be employed the mixture becomes short, difficult to mould, and is excessively friable when dry and liable to break in handling. In England the common practice in the manufacture of large refractory articles, such as tank blocks for glass furnaces, is to use about 30 per cent grog. Although it is generally the case that mixtures of high grog content are very porous, with judicious grading and the use of only hard-fired dense grog it is possible to obtain a dense block containing considerably more than 30 per cent grog, satisfactory blocks being found containing over 50 per cent grog.

Refractories containing up to and over 80 per cent of grog are made for special purposes, and in this class are included special refractories, such as silicon carbide (carborundum) and aluminous articles.

In grinding grog attention should be given to the adjustment of the grinders to yield grog as angular as possible. Smooth, rounded grains make weaker bodies and do not bind with such facility as angular particles, requiring more binding clay. It is partly for this reason that the incorporation of carborundum into a clay mix effects a great increase in the strength of the body.

It is usually found desirable, in making the best class of refractories, to use a mixture of several clays, one, highly refractory, blended with a clay not so refractory but very plastic. Such a practice is found, among other advantages, to produce a denser and stronger body and to distribute the shrinkage during the firing over a longer temperature range, thus reducing the danger of warping and cracking owing to small variations in temperature in different parts of the kiln.

Having selected suitable clays and determined the proportion and grading of grog, the mixture is weighed out or measured by volume (if the grog has not previously been ground in with the clay) and, as a rule, put through some form of mechanical mixer, "pug-mill" or "blunger." Sometimes the mixing is carried out in a mill of the edge runner type with a revolving pan which contains no perforations. The runners are of a lighter construction than those used for crushing and are suspended on bearings to avoid further crushing of the grog. It is more usual to employ a mixing trough, fitted with revolving blades which propel the mixture slowly along the trough while the mixing is being carried out. The troughs may be open or closed

(pug-mill), the latter type being mounted vertically or horizontally. Water is added to the clay in the mixer to form a plastic mass of the desired consistency for moulding. After pugging, the clay is sometimes considered ready for moulding, but more frequently it is laid aside in a cool place to "sour" for a period of anything from a few days to some months. The clay is kept moist during this time, usually covered with sacking. This process undoubtedly improves the plasticity and distributes the moisture more evenly through the mass.

The moulding of refractories is generally carried out in wooden or metal moulds (for some purposes plaster of Paris moulds are sometimes used). For large blocks the sides of the mould are fastened together by means of hooks and can be taken apart after the block has been finished and allowed to harden.

The clay is thrown with force into the mould, working with small quantities at a time, from the corners and edges inwards, and is tamped thoroughly in position.

The surfaces of the blocks are subsequently smoothed with a scraper. Bricks and small articles can be moulded in single part moulds which can be filled at one "throw." Hollow blocks are moulded with the use of cores in the mould. It is sometimes found desirable, when making blocks of inconvenient shapes, to mould a block somewhat larger than the required size, to allow it to dry slightly, and then to carve it to the finished shape.

(ii.) *Pressing.*—For many purposes forming by pressing gives results more satisfactory than by plastic moulding. In the first place, it is unnecessary to use highly plastic clay, a higher percentage of grog can be used if desired, the drying shrinkage is small, and the resulting body more dense. There is a limit to the pressure which can be applied with good results to clay refractories for any particular moisture content. If this pressure is exceeded a laminated structure is produced. The drier the clay the more pressure it will stand. The maximum density is obtained if the clay is slightly damp.

Until recently there has been a prejudice against machine-made bricks and blocks. This has arisen owing to the difficulty of securing the exact conditions necessary for obtaining good pressed ware. The distribution of pressure, the most suitable load, and the time of application must be adjusted to suit the particular material which is being worked, and if these adjustments are at fault, articles will be produced which will compare unfavourably with hand-made ware.

It has not yet been found practicable to produce by pressing very large blocks of complicated shapes, although pressed blocks would offer many advantages, notably uniformity to the specified dimensions, since these blocks do not shrink appreciably while drying and are less liable to warp in firing if the materials are well mixed.

The manufacture of pressed bricks has been established for some time, and it has been found that the well-made pressed brick is equal, if not superior, to a good hand-made brick and is generally truer to shape. The output of up-to-date brick machines may be very large, up to 1000 bricks per hour.

(iii.) *Casting.*—The process of slip-casting is largely used in the manufacture of pottery and porcelain, but at present it has had only a comparatively small application to the fireclay industry. The procedure adopted where no core is employed is as follows: Water is added to the clay mixture until a viscous liquid is produced, just sufficiently fluid to be poured from the containing vessel into the mould. If the liquid is too thin the coarser particles of the clay and grog will settle at the bottom. The mould is made of plaster of Paris, which absorbs the water from the slip, leaving a layer of semi-dry clay on the surface of the mould. When the layer has reached the required thickness the remaining slip is poured out, leaving the solidified clay adhering to the mould. After a short time the clay shrinks slightly and becomes detached from the mould; the article is then removed from the mould and allowed to dry in the usual way.

§ (12) Preparation of the Mould for Casting.—A pattern of the refractory article required is made in wood, clay, or metal (due allowance being made for the shrinkage of the refractory on firing), and round this pattern a mould is cast, with a fine grade of plaster of Paris; the pattern is lubricated to prevent the adhesion of the plaster (a solution of soft soap is commonly used as a lubricant). It is generally found necessary to make the mould in several parts to facilitate the removal of the clay casting which is fragile. In casting complicated shapes it is sometimes necessary to make the mould in six, eight, or even more parts. When casting large articles and the mould requires to be of considerable size it is customary to reinforce it with iron rods or to enclose it in a wooden case.

The thickness of the mould depends on the thickness of the refractory being cast, *i.e.* on the amount of water to be absorbed, an average thickness for articles such as small crucibles being 2-4 inches. For casting large articles, the plaster walls may be 6-10 inches thick, or even more.

§ (13) Preparation of Slip.—The preparation of a slip is a comparatively simple matter and requires far less care and expenditure of time than the preparation of the plastic mixture for moulding. The desired quantities

of clay and graded grog are weighed out and mixed with water and a small quantity of a deflocculating agent (see § (7)) in some form of "blunger." Slips made up from a highly plastic clay do not, as a rule, cast well, although a small proportion of plastic clay added to the mixture facilitates the casting slightly. The grog content of the slip is as a rule high—from 40 to 60 per cent. The addition of the deflocculator decreases the viscosity of the slip greatly, thus enabling less water to be used and increasing the weight of the slip. It is desirable to use a slip as thick as will pour conveniently, to prevent settlement of the coarser particles of grog. It is common practice to use about one-fifth per cent of the deflocculant (calculated on the total dry weight of clay). Sodium carbonate or sodium silicate are the most usual reagents; a mixture of the two gives the best results (roughly two parts of sodium carbonate to one part sodium silicate), but the choice of the deflocculants varies somewhat with the clays used.

Without the use of a deflocculant, an average slip weighs up to 26 or 28 ounces to the pint. With the addition of a suitable reagent slips can be made weighing 36 ounces to the pint or even more and containing only about 20 per cent water. The use of these heavy slips has many advantages. The grog does not tend to settle, the plaster moulds do not become rapidly saturated with water and can be used several times without drying, and the time of casting is shortened; it is also possible to cast articles thicker with the deflocculated slip than with the simple slip.

§ (14) Details of Casting Processes.—It is not as a rule convenient to cast without a core bodies having a wall thickness greater than 1½″ to 2″. By having a plaster core this thickness can be increased to about 3″ to 4″. Thick articles take some hours to cast and require to be left in the mould over-night before they are sufficiently dry and acquire the necessary strength to enable them to be removed from the mould. If a plastic clay be used the thickness of wall which can be cast is greatly reduced. Great advantages are claimed (apparently justifiably) for the process of vacuum casting, in which the mould is enclosed in a chamber which can be evacuated. The moisture is thus drawn off rapidly and the casting greatly accelerated; the articles cast in this way are practically dry before leaving the mould, only a short time for further drying being necessary before firing. (Further advantages are obtained by introducing the slip into the mould under pressure—from 10 to 20 lbs.) By this process it has been found possible to cast articles considerably thicker than in the ordinary way. The advantages of slip casting are:

The process is rapid both with respect to the preparation of the clay and the time of manufacture, skilled labour is not required, non-plastic mixtures can be used, and the time of drying and the risk of cracking during this time are reduced. On the other hand, the moulds are bulky and expensive—particularly when vacuum or pressure casting is employed. Great care has to be exercised when storing the moulds to avoid disintegration of the plaster, especially if a deflocculant is used.

§ (15) Drying.—The drying of large pieces made from a plastic mixture is a tedious and delicate process. In the case of small articles, such as standard firebricks, comparatively rapid drying may be practised. With well-regulated heating and ventilation, bricks may be dried in three to four days, or less if a tunnel drying kiln is used. Very roughly, the time required for drying varies as the ratio of the volume of the article to the superficial area. Large blocks, however, are extremely difficult to dry completely, requiring very careful regulation of temperature, and ventilation, and absence of draughts. A large block may take anything up to six or eight months to dry.

A process which promises to give good results is known as "humidity drying." The blocks are placed in a chamber and heated, steam being introduced into the chamber at the same time. A high temperature is maintained during the process and the humidity of the atmosphere gradually reduced. In this way the water vapour passes out from the inside of the blocks while the outside is still damp and little or no shrinkage has occurred. This process is not yet in general use, although it has been tried, with considerable success, in certain cases.

Lack of caution in the drying may cause cracking or warping during the firing. The phenomenon of "black coring" may also be traced indirectly to this cause. It is frequently found that in the centre of large fire-clay blocks a dark vitrified zone exists. This dark patch is due chiefly to the presence of ferrous silicates and carbonaceous material which has not been burnt out during the firing, and indicates the lack of oxidising conditions during the early part of the firing.

It is essential that all refractories, particularly those containing appreciable quantities of carbonaceous materials, should be fired slowly during the stage from 500° to 700°, to permit of thorough oxidation; if this is not done, fusible ferrous silicates will be formed and the refractoriness of the block impaired. The presence of moisture in the clay will cause a lag between the temperature of the kiln, which is raised steadily, and that of the refractory, with the result that, when the water is finally expelled, the temperature of the block rises rapidly, passing through the danger zone too quickly. The risk of black coring could be avoided by slower firing, but the cost of

fuel deters the manufacturer from providing a safety factor which, if the drying were satisfactory, would be unnecessary.

§ (16) Firing. *Kilns.*—Many types of kilns are employed for the firing of refractories. These fall into three groups: (i.) up-draught kilns, (ii.) down-draught kilns, (iii.) horizontal-draught kilns.

(i.) *Up-draught Kilns.*—In these the gases enter the base of the kiln, pass up through the refractories, which are packed in the kiln in such a manner as to leave suitable passages, and out through an outlet in the crown of the kiln. It is not easy to obtain either a high or an even distribution of temperature in these kilns and they are little used now.

(ii.) *Down-draught Kilns.*—This is the type usually adopted for firing all classes of refractories. These may be either gas or direct coal fired. For firing large blocks or bricks required to be burned to a high temperature, kilns built as a single unit are used. These are usually circular in plan; the gas passes in at the base of the kiln and proceeds up through flues in the wall placed symmetrically at intervals round the periphery. The flame strikes the crown and the products of combustion are deflected downwards, passing between the blocks under fire and so out through a flue leading from the base of the kiln to the stack. Sometimes a separate stack is dispensed with, a cone being built over the kiln and the waste gases being led by radial horizontal flues under the kiln and then up through flues in the walls leading to the cone.

In these down-draught kilns it is possible to maintain a careful regulation of the temperature of firing and the distribution of temperature is uniform, although the kiln is usually hotter at the top than at the bottom, particularly in the final stages of the firing. Great care must be exercised in the suitable packing of the kiln, especially if large blocks are being fired, since the evenness of the temperature distribution and the consequent freedom from warping depends largely on the spaces left for the passage of the flames and also on the manner in which the blocks are supported. Single kilns are wasteful of fuel and a great economy is effected by coupling a number of kilns together, arranging that the waste gases are led through the chambers containing the refractories which are being dried and are in the early stages of firing and that the air for combustion is preheated by drawing it through the chambers which are cooling down. Such an arrangement may result in the saving of over 50 per cent of the fuel.

Several well-known types of continuous kilns are in successful operation, embodying the above principle, but in general it is only practicable to use a continuous system where the output is large and of a uniform type, such as a stock size of firebricks.

(iii.) *Horizontal-draught Kilns.*—These are used extensively for burning firebricks, but are not very successful if high temperatures are required, since it is not easy to obtain uniformity of temperature and firing conditions. These kilns consist of rectangular chambers with fireboxes at one end and the flues to the stack at the other. Large kilns may have fires at each end, and exit flues at the centre of the kiln. Owing to the short path of the flame these kilns, as single units, are wasteful of fuel—much heat passing out through the stack—but, used in series to form a continuous kiln, this heat may be recovered.

Regenerative kilns are not used very greatly in the refractories industry; they are, however, employed occasionally where extremely high burning temperatures are required, as in the best grade of magnesite bricks.

A type of kiln which is becoming popular in some branches of the industry is the tunnel kiln. This consists of a long tunnel heated to the desired maximum firing temperature in a central zone. The refractories to be fired pass on trolleys slowly down the tunnel and are preheated before entering the central firebox by the waste products of combustion which pass down the kiln to meet the incoming trolleys. The air for combustion in the central firebox is preheated, deriving its heat from the cooling refractories as they pass on down the kiln after traversing the central heating zone. It is possible in these kilns to control the rate of heating with considerable accuracy, since it is only necessary to maintain a steady temperature in the kiln, when, if it has been well designed, the correct rate of heating is assured and, in consequence, the refractories may be drawn through the kiln comparatively rapidly, there being no fear of a sudden rise of temperature at a stage in the firing when this might be dangerous. The output of these kilns is very large, but they have serious limitations; at present it has not been found practicable to attain the highest temperatures required, and even when this difficulty has been overcome it will not be easy to fire a large range of sizes of articles at the same time.

The electric furnace has not yet found any appreciable application for firing refractories on a commercial scale.

§ (17) Firing Schedule.—The firing schedule of fireclay refractories may be divided into three stages—the drying or "smoking" stage, the decomposition stage, and the full firing. If the blocks have been given a prolonged period for drying in a warm well-ventilated room, the first stage (up to about 110° C.) need occupy not more than twenty-four hours—with small articles considerably less. If, however, there is any reason to doubt the efficacy of the drying, the smoking stage must be carried out with great caution. After passing,

say, 200° C. the rate of heating may be increased somewhat until a temperature of from 400° to 450° is reached, then the second stage of firing begins. Over a range of from 400° to 450° the clay molecule breaks down (see § (8)), the chemically combined water is liberated, and the organic matter present in the clay is oxidised. The rate of heating is retarded during this stage and should not exceed 5° C. per hour. Sometimes the kiln is held at a steady temperature in this region to ensure that the oxidation may be complete to the heart of the block.

From 700° to 1050° C. the temperature may be increased rapidly. In the neighbourhood of 1100° C. the third stage of the firing is begun. From this point up to the maximum temperature of firing vitrification and shrinkage occurs, the fluxes melt and dissolve the less fusible constituents.

In general the shrinkage and decrease in porosity of clays in firing is roughly proportional to the content of fluxes (Ca, Mg, K, Na, etc.) in the clay. The texture of the clay, the grading of the clay particles and of the grog play an important part, however; the ratio of silica and alumina also influences the behaviour of the clay in firing. The drying and firing shrinkage of clays containing no grog is of the order of 10-15 per cent, roughly, half this shrinkage occurring during the drying. Clays loaded with a high percentage of grog—exceeding 50 per cent — may show no appreciable shrinkage if the grog be well burnt. The amount of the shrinkage and the apparent porosity (see § (9)) varies considerably with the rate of drying and firing.

III. Properties of Clay Refractories

§ (18) Refractoriness or Softening-point. —It will be seen from § (1) that it is impossible to tabulate precisely the broad property of refractoriness in a satisfactory manner. What is known as the "normal refractoriness" (*i.e.* the comparison of the behaviour of a cone cut or moulded from the clay under test with a Seger Cone (see § (3)) under a standard rate of heating) gives but little indication of the softening-point of a refractory under working conditions. For example, if the refractory be subjected to a load its squatting temperature under the load cannot be predicted with any certainty from the normal refractoriness, although by an examination of the texture and the chemical composition, coupled with a knowledge of the firing temperature, we may make an approximation. Further, under working conditions, refractories are almost always exposed to corrosion in some form, either to the action of slags, glass, etc., corrosive vapours, or to dust carried by the fuel. A porous refractory will absorb fluxes from one or other of these sources, and its effective refractoriness will be dependent on the amount and the nature of the fluxes which penetrate into the pores. It follows that a refractory of open texture which gives a high normal refractoriness in a laboratory test may have a lower refractoriness in use than a denser block which was initially of a lower refractory standard, but which was non-absorbent. On the other hand, under a clean heat, an open texture is a desirable attribute for refractoriness.

We may divide clays into several grades for convenience in classification:

Grade I. Refractoriness greater than Cone 34, ° C.
Grade II. Refractoriness greater than Cone 30, ° C.
Grade III. Refractoriness greater than Cone 26, ° C.

Materials softening below Cone 26 cannot be regarded as refractory. Grade **I.** is for use where extreme temperatures necessitate the use of the highest quality of clay, Grade II. where the working temperatures do not exceed 1350° C. and it is desirable to sacrifice refractoriness for some other property. Grade III. is suitable for the construction of flues, regenerators (at cool end), etc.

§ (19).—Below are given analyses of typical clays together with their normal refractoriness.

	SiO_2.	Al_2O_3.	TiO_2.	Fe_2O_3.	CaO.	MgO.	K_2O.	Na_2O.	Loss.	Refractoriness Cone.	
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.		
Gross almerode .	73·08	15·75	2·10	0·62	0·54	0·33	0·27	0·16	7·11	28	(1630°)
Klingenberg . .	50·76	29·26	1·61	1·51	1·08	0·73	0·85	0·19	14·24	30	(1670°)
China clay . .	48·31	37·08	nil	0·77	0·44	0·36	0·92	0·38	11·84	35	(1770°)
Halifax clay . .	60·39	24·10	1·19	2·56	0·68	0·50	0·40	0·22	10·11	30	(1670°)
Stourbridge clay .	57·43	25·22	1·16	1·40	0·56	0·68	1·16	0·84	10·32	31	(1690°)
Derby clay . .	50·76	30·18	1·39	1·68	0·58	0·72	2·60	0·64	11·67	31	(1690°)
Bauxitic clay . .	41·60	37·08	4·13	1·43	0·53	0·19	0·64	0·32	14·06	33-34	(1740°)

Attempts to derive a formula from which the refractoriness can be calculated from the chemical composition have not been very successful. The higher the silica content of the clay the less the refractoriness and the less the amount of fluxes which the clay will bear without undue loss of refractoriness. The diagram (*Fig.* 1) shows the liquidus of the

$SiO_2 - Al_2O_3$ system. It will be seen that within the range of common clays the refractoriness decreases steadily with the addition of silica to the clay, reaching a eutectic point at a composition corresponding to a formula $Al_2O_3\,17SiO_2$ (the softening-point of the eutectic mixture is Cone 26) (1580°). The addition of fluxes, while lowering the softening-point, displaces the eutectic towards the alumina end. (Lithia appears to be an exception, the eutectic moving to the left.) It was formerly assumed that molecularly equivalent amounts of fluxes

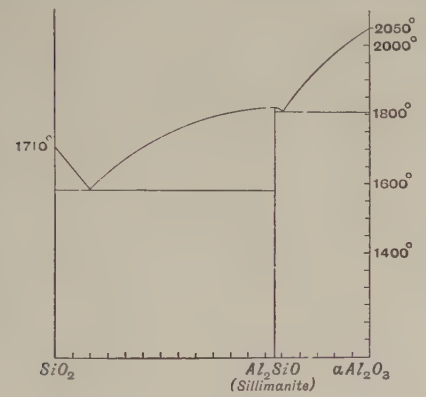

FIG. 1.

lowered the softening-points of clays an equal degree (Richter's Law). This is approximately true where the fluxes are present in small amounts only—not much exceeding the quantities found in natural clays (1). It is found, however, (2) that molecular equivalents of fluxes of low molecular weights depress the softening-point further than do those of high molecular weight.

The following diagram (Ludwig) (*Fig.* 2) affords a useful scale of comparison of the refractoriness of different clays.

The effect of the addition of various fluxes, titania (3), (4), lime (9), (10), magnesia (11), iron oxide (5), and the alkalis (6), (7), (8), etc., has been studied in detail by various workers.

From the above considerations it is seen that the more alumina a clay contains, the higher the percentage of fluxes the clay can hold for any given standard of refractoriness. It is impracticable, however, to add alumina to clays on an industrial scale to improve the refractoriness, since there is a scarcity of sources of alumina free from fluxes (notably iron). There are a variety of sources of high-grade silica, almost free from fluxes, and we find, therefore, that it is sometimes advantageous to add silica to clays which contain a high percentage of fluxes, since the effect of the addition of silica, the lowering of the softening-point by the increase of the silica-alumina ratio, is more than counterbalanced by the decrease in the total content of fluxes in the mixture produced by the dilution with a pure material.

If, however, the refractory is for use under working conditions where it will come into contact with an excess of fluxes, then the addition of silica is attendant with risks, since a high percentage of silica in conjunction with a high flux content is very detrimental.

§ (20) SOFTENING-POINT UNDER LOAD.—The softening-point of all clay refractories falls rapidly if tested under an increasing load. It is generally observed that clays high in silica will stand the load better than those high in alumina.

The presence of fluxes exerts a powerful influence on the load-carrying capacity, the effect varying with the alumina-silica ratio in the clay. Bleininger and Brown [1] testing samples of commercial American bricks and clays at 1300° C. under 75 lbs. per sq. inch, and at 1350° C. under 50 lbs. per sq. inch, found that none of the clays tested would pass these tests if the fluxes exceeded 0·22 molecule to 1 mol. alumina when the alumina-silica ratio was 1/3, or 0·17 mol. of fluxes with an alumina-silica ratio of 1/4·4. Although the total flux content of a clay may give an indication as to its load-carrying capacity, the distribution of

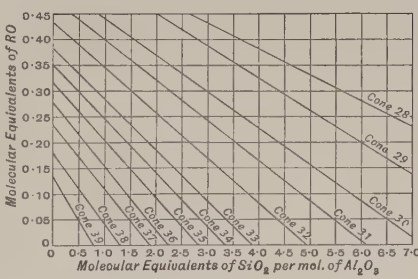

FIG. 2.

RO represents the basic oxides, Na_2O, K_2O, CaO, etc.

the fluxes and the amount of infusible material they have taken into solution during the firing play an important part. For example, many clays high in iron may give high softening-points under load if the iron is not widely segregated but found in nodules in the clay.

Mellor has established that in the case of fireclays the relation between the load and the squatting temperature is satisfied by the empirical equation $R = Ce^{-KW}$, where R is the refractoriness under a load W (lbs. per sq. inch), C being the normal refractoriness and K a constant characteristic of each clay. Carrying out tests on a series of typical clays under similar conditions as regards preparation of specimens, rate of heating, and so on, he assigned values to K from 0·0110 to 0·0030.

[1] *Tech. Paper, Bureau of Standards, U.S.A.*, No. 7.

As might be expected, the softening-point under load is greatly affected by the quantity and grading of the grog and also by the firing temperature, the latter being particularly important in the case of aluminous refractories. The failure of many aluminous clays under load is due to the fact that they have been underfired and it is quite possible to make aluminous refractories which will give excellent service under load if a sufficiently high firing temperature be attained.

With so many variables affecting the behaviour of clays under load it is impossible in the space available to give even a summary of the data correlating the softening-point under varying loads with the alumina-silica ratio, amount and composition of fluxes, texture, grog content, and firing temperature. To give an example of the behaviour under load in relation to variations in composition, etc., we may cite these clays examined by Mellor.[1]

	(1)	(2)	(3)
SiO_2 . . .	53·84	51·24	61·88
Al_2O_3 . . .	25·73	28·06	22·37
TiO_2 . . .	1·32	1·39	1·14
Fe_2O_3 . . .	5·25	1·89	3·00
MgO . . .	0·83	0·33	0·44
CaO . . .	0·44	0·40	0·32
K_2O . . .	1·48	0·20	0·42
Na_2O . . .	0·27	0·24	0·36
Loss on ignition .	11·04	15·74	8·72

These clays were made up with their own grog (fired to Cone 10, Temp. 1300° C.). The test pieces were fired to Cone 10. The table below gives the refractoriness under load of 50 lbs. per sq. inch for the various grog mixtures together with the normal refractoriness, *i.e.* that under no load.

	Refractoriness under load of 50 lbs. per sq. in.		
	(1)	(2)	(3)
A. 1 part clay, 1 part fine grog	13-14	10-11	8
B. 1 „ „ 1 „ medium „	13-14	13-14	9-10
C. 1 „ „ 1 „ coarse „	13-14	8	10-11
D. 3 „ „ 2 „ fine „	14-15	12	11
E. 3 „ „ 2 „ medium „	14-15	10	10
F. 3 „ „ 2 „ coarse „	13	10	11
G. 2 „ „ 1 „ fine „	13	9	13-14
H. 2 „ „ 1 „ medium „	13-14	8	13-14
I. 2 „ „ 1 „ coarse „	13	9	13
Normal refractoriness , . .	20-26 (1550° C.)	31 (1690° C.)	20-27 (1530°-1610° C.)

It will be noted that No. 2, the most refractory under no load, is inferior to No. 1 under load. Fired to Cone 15-16 instead of to Cone 10, however, No. 2 (G mixing) softened at Cone 14-15 under load.

[1] Mellor and Emery, *Trans. Cer. Soc.* xv. 117, xvii. 360, 368.

§ (21) Crushing Strength.—The crushing strength of refractory materials is governed largely by the texture and conditions of firing. The strength of the average firebrick in the cold varies from 2000 to 6000 lbs. per sq. inch,[2] and in exceptional cases may exceed 10,000 lbs. Silica bricks have a crushing strength slightly lower than firebricks. Specifications for the strength of firebricks are usually low; thus, the Institute of Gas Engineers specify a maximum of 1800 lbs. per sq. inch and the Bureau of Standards, U.S.A., specify 1000 lbs. per sq. inch as the minimum for their first-quality brick. A high crushing strength is usually associated with a low refractoriness, since it denotes the presence of a vitrified bond and indicates that the clay vitrified at the temperature at which it was fired, which is comparatively low.[3]

In general a high crushing strength in the cold is not important, the failure of the refractory usually occurring at high temperatures.

Exposure to weather reduces the strength of refractories greatly. It has been stated that five days' exposure to rain (without frost) may reduce the strength of porous firebricks to four-fifths of its original value, while one night's frost on a wet brick may reduce its strength by three-quarters. These figures are exceptionally high. An average firebrick after six months' exposure may lose anything from 1 to 25 per cent of its strength. With silica bricks the disintegration on weathering is rather more severe. Generally speaking, the more porous the refractory, the more severe will be the effect of weathering. Very dense bricks may suffer little or no harm on exposure.

§ (22) Strength of Unfired Clay.—The strength of dried, unfired clay bodies is of interest, since it is a comparative measure of the plasticity of the clay and affords an indication of the liability to fracture in handling before firing. The tensile strength, crushing strength, and modulus of rupture are generally determined. Of the three the modulus of rupture appears to give the most concordant results.[4] This test is usually carried out on briquettes about $1'' \times 1'' \times 7''$ and the modulus calculated from the formula

[2] Tested on the flat; tested on edge or on end the strength will be about 30 per cent lower.

[3] For any particular clay with a fixed percentage by weight of grog, the strength will be proportional to the surface factor of the grog.

[4] Bleininger and Howat, *Trans. Am. Cer. Soc.* xvi. 273.

$M = 3Fl/2bd$, where F is the force applied (lbs.), l the distance between the supports, b and d the width and depth of the bar. Great care is necessary in the drying of the specimens, since, with the plastic clays, the drying shrinkage-cracks, which are always formed to some extent, lead to unreliable results. For making comparative tests on different clays, the practice of mixing the clays with an equal weight of uniformly graded sand is sometimes adopted. This removes the danger of errors through drying cracks in the more plastic clays. With excessively plastic clays, the sand mixture gives a modulus of rupture considerably higher (up to 100 per cent) than the clay without dilution, even with careful drying.

The modulus of rupture of plastic clays varies between 250 and 1000 lbs. per sq. inch. With less plastic clays the modulus may fall to as low as 100, china clays lying between 50 and 150. The tensile strength of plastic clays ranges from 20 to 100 lbs. per sq. inch. The strength of clays in compression varies from 200 to 1200 lbs. per sq. inch; these values are for carefully dried clays containing no grog. The strength may be increased by many times its former value by fine grinding before briquetting.

With the addition of grog, the strength varies with the grading of the grog, being roughly inversely proportional to the porosity. Suitable grading of grog may increase the strength up to 100 per cent of the ungraded mixture.

§ (23) Variation of Strength with Temperature.—With an increase in temperature the strength of siliceous and aluminous refractories falls steadily until it reaches a well-defined minimum [1] in the neighbourhood of 800° C. (in some cases it may be as low as 600° C. or as high as 1000° C.). The temperature at which this minimum occurs does not vary considerably with the temperature to which the refractory has been originally fired. With an increase in temperature the strength increases rapidly, reaching a maximum usually from 100° to 200° C. above the temperature at which the minimum occurred. On further increasing the temperature there is a rapid falling off in the strength, and we approach the softening-point of the refractory under load (see § (20)).

The cause of the phenomenon is obscure; it has been noted in clays and also in corundum, fused silica, and carborundum. This discontinuity of mechanical properties just below the softening-point has a curious parallel in the discontinuity in the coefficient of expansion of glass just below its "softening-point."

The strength of a refractory at this maximum may be many times the strength of the refractory when cold. In *Figs.* 3 and 4 are given

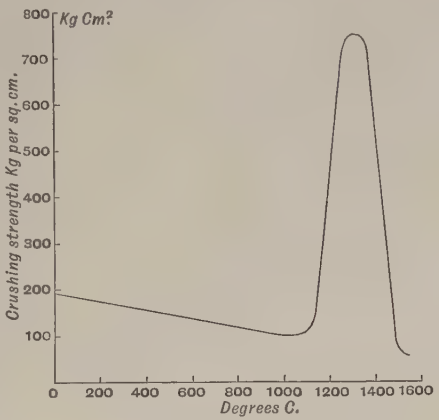

Fig. 3.

two typical strength-temperature curves taken from Bodin.

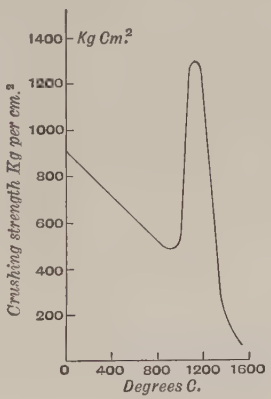

Fig. 4.

§ (24) Coefficient of Expansion.—The coefficient of expansion of hard-fired clay bodies is governed by the chemical composition of the clay. Thus, silica imparts a low coefficient of expansion to a clay (when hard-fired), alumina a high. The temperature-expansion curves are approximately linear up to 1000° C. The mean coefficients of expansion (0°-1000° C.) lie between $2{\cdot}8 \times 10^{-6}$ and $4{\cdot}5 \times 10^{-6}$. Clays or mixtures which have not been very hard fired, not exceeding, say, Cone 14 (1410° C.), exhibit discontinuities in expansion over certain temperature ranges, the expansion depending not only on the ultimate composition of the clay, but on the heat treatment which it has received. The effect of heat treatment on the coefficient of expansion of

[1] Bodin, *Trans. Cer. Soc.* xxi. 44.

refractories has been examined by Houldsworth and Cobb.[1]

In kaolin or a highly aluminous clay or shale the expansion of specimens fired to Cone 06 (980° C.) is almost uniform from 0° to 1000°, the mean coefficient being $4{\cdot}0 \times 10^{-6}$. This indicates that if we accept the theory that kaolin decomposes in the neighbourhood of 500° C., forming free alumina and silica,[2] the latter must be in an amorphous state, since there is no indication of an increase in the expansion between 500° and 600° due to the presence of quartz or at a lower temperature due to the $\alpha\ \beta$ transformation of cristobalite or tridymite (see § (30)). If the specimen is now fired to Cone 9 (1280°) a small fraction of the silica appears to be converted to cristobalite, and we find a slight increase in the expansion between 150° and 250°, the mean coefficient between 100° and 250° being $7{\cdot}64 \times 10^{-6}$. With an increase in the firing temperature to Cone 14 (1410°), the silica appears to go partly into solid solution and the discontinuity in the expansion from 150° to 250° tends to disappear, the mean coefficient between 100° and 250° falling to 5·78 and between 15° and 1000° to 4·77. With a high firing temperature, Cone 20 (1530° C.), all traces of silica inversions disappear—the temperature-expansion curve lying near to the curve for the kaolin fired to Cone 06. If amorphous precipitated silica is intimately mixed with the kaolin, the expansion of the kaolin is unaffected, although the silica alone would have become, under similar heat treatment, partially converted to cristobalite, and the abnormal expansion ($\alpha\ \beta$ cristobalite inversion) would have been found between 150° and 250°. This evidence supports the theory of the formation of free silica on the decomposition of the clayite molecule, since it shows that free silica may remain apparently in solid solution without transformation to a crystalline form which can be recognised by its physical properties.

The temperature-expansion curves of alumina are similar to those of kaolin, the numerical value of the coefficient being higher, however, in the case of alumina, as would be expected.

Most fireclays contain free quartz, and we find, accordingly, that the expansion curves show evidence of the $\alpha\ \beta$ quartz transformation between 500° and 600° on firing to Cone 06. In fireclays fired to Cone 9, a part of the quartz is converted to cristobalite, and we have, therefore, an increased expansion from 150° to 250° in addition to the $\alpha\ \beta$ quartz inversion. If the firing temperature is raised to Cone 14, the expansions due to the inversions of silica are diminished, since the crystalline silica will be partially taken into solution by the fluxes which have fused at this firing temperature. At Cone 20 all the crystalline silica will have been dissolved, and we shall obtain a smooth curve similar to the curves for kaolin fired to Cone 06 and Cone 20. *Fig.* 5 shows typical curves illustrating these phenomena for a fireclay of the following composition :

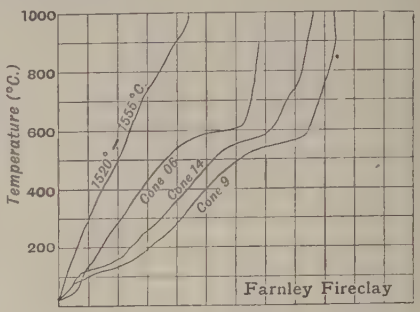

FIG. 5.

Loss on ignition	9·36
Silica	63·48
Alumina	22·39
Titania	1·10
Ferric oxide	1·33
Lime (CaO)	0·70
Magnesia	0·52
Soda (Na_2O)	0·88
Potash (K_2O)	0·65

The following table gives the coefficients of expansion ($\times 10^{-6}$) of specimens fired to Cone 06, 9, 14, 20 respectively.

Temp. Range.	Firing Temperature.			
	Cone 06.	Cone 9.	Cone 14.	Cone 20.
	(980° C.)	(128° C.)	(1410° C.)	(1530° C.)
100°- 250°	..	10·23	8·75	..
15°- 500°	4·81	7·69	6·76	..
500°- 600°	13·31	12·75	10·75	..
600°-1000°	2·17	1·83	2·50	..
15°-1000°	4·91	5·83	5·40	3·05

In a finely divided plastic clay, such as a ball clay, or in a clay rich in fluxes, a smooth curve is obtained with a lower firing temperature (say, Cone 14), since the complete solution of the crystalline phases is more readily obtained.

An interesting phenomenon is associated with the $\alpha\ \beta$ quartz transformation. It is found that in both silica and siliceous clays the heating and cooling curves do not coincide, the contraction on cooling from 600° to 500° being greater in every case. In this range the co-

[1] Mellor and Holdcroft, *Clay and Pottery Industries*, i. 272 *et seq.*

[2] Houldsworth and Cobb, *Jour. Soc. Glass Tech.* iii. 201, v. 18.

efficient of contraction may be anything from 20 to 40 per cent greater than the coefficient of expansion.

An increase in porosity decreases the coefficient of expansion appreciably. Houldsworth and Cobb give the following example. The porosity was increased by mixing rape seed with the raw clay, which was then fired to Cone 9.

Porosity.	Coefficient of Expansion (15°-1000°).
Per cent.	
28·7	$5{\cdot}83\times10^{-6}$
44·6	$5{\cdot}17\times10^{-6}$
50·2	$4{\cdot}91\times10^{-6}$

A further increase in porosity made no appreciable difference.

§ (25) Porosity (see § (9)).—The porosity of a fireclay is governed by the refractoriness of the clay, the percentage and grading of the grog, the firing temperature, and (particularly in the case of dense burning clays) the rate of heating. A fireclay free from grog will have a porosity when lightly fired to, say, 650° C. of from 20 to 35 per cent. The porosity of kaolin fired to this temperature will be from 45 to 55 per cent. The porosity decreases with a rise in temperature as the fluxes melt until the apparent porosity (§ (9)) approaches zero. The addition of grog to a highly plastic clay may decrease the porosity in a lightly fired block, since the grog inhibits the shrinkage cracks which occur in drying giving rise to an increase in porosity. In general, however, the porosity of a clay body fired to 600° will be increased by about 5 per cent by the addition of the maximum amount of grog which the clay will hold without becoming too "short" to work with (from 20 to 50 per cent grog). As the firing temperature increases, the effect of the grog becomes more pronounced; thus, the addition of, say, 40 per cent of grog may increase the porosity of a clay from 14 to 26 per cent, from 10 to 24 per cent, from 8 to 22 per cent, from 5 to 20 per cent. With a high grog content the rate of heating does not greatly affect the porosity, but where the difference between the true and apparent porosity (§ (9)) is large the rate of heating may have an appreciable effect.

The porosity of fireclay bricks or blocks varies from 8 to 30 per cent. On an average, the porosity lies between 18 per cent and 24 per cent. The higher the porosity the weaker the block is mechanically, but the more resistant to change of temperature and the more elastic. A porous block is, as a rule, more susceptible to corrosion, possesses a low thermal conductivity, and is more refractory in the absence of fluxing agents—such as flue dust or slag. Unless made for some special purpose the porosity should not exceed 25 per cent, and where exposed to a slagging action should not exceed 18 per cent. It is important to note that rapid heating of clay bodies of low grog content and porosity give rise to strain and mechanical disintegration, and in consequence the properties associated with a high or low porosity outlined above are, in many cases, reversed. For example, it is found that rods used for stirring slags, or glass, or troughs through which a slag flows, will, in cases where, for practical consideration, it is found necessary to raise the temperature of the rod or trough faster than a certain critical rate, stand the corrosion and mechanical shock better when a highly porous (though hard-fired) body is used.

§ (26) Specific Gravity.—The specific gravity of raw clays lies between 2·4 and 2·6. On heating, the specific gravity rises to a maximum and then falls. This maximum occurs at the point where vitrification of the clay begins; the specific gravity is therefore a valuable guide to the changes occurring on firing. In the examination of a clay the specific gravity-temperature curve is in some ways more satisfactory as an indication of the progress of vitrification than the porosity-temperature curve, since in the former case the rate of heating of the specimen does not cause such variations in the slope of the curve. The maximum specific gravity varies from 2·75 to 2·48 as the alumina content diminishes. In a well-sintered clay the specific gravity may fall, on an average, 0·15, and with a hard firing 0·20 or more.

§ (27) Specific Heat.—The specific heat of firebricks is approximately 0·20 C.G.S. unit from 0° to 100° C., but rises rapidly with temperature. Bradshaw and Emery give a value for the mean specific heat of fireclays of $\cdot194+\cdot000075t°$. The following table gives values obtained by Bradshaw and Emery,[1] and Heyn, Bauer, and Wetzel.[2]

Mean specific heat, 20° C. – t° C.

Temperature.	Sp. ht. B. & E.	Sp. ht. H., B. & W.
$t°=$ 200°	..	·204
400°	·228	·222
600°	..	·236
800°	..	·248
1000°	·265	·256
1200°	·284	·263
1400°	·297	..

[1] Bradshaw and Emery, *Trans. Cer. Soc.* xix. 84.

[2] Heyn, Bauer, and Wetzel, *Mitteil. a. d. Königl. Materialprüfungsamt*, Berlin, Lichterfelde, 1914, 39, 89.

CONDUCTIVITY (THERMAL)[1]

	Temperature °C.	K × 10⁴ C.G.S. Units.	Authority.
Fireclay Bricks—			
66% SiO_2 : 29% Al_2O_3 } burnt at	230-1160	35·0	Wologdine, 1909.
4% Fe_2O_3 : 0·5% CaO } 1050° C.			
Ditto . (burnt at 1300° C.)	230-1000	42·0	
66% SiO_2 : 31% Al_2O_3 } burnt at	600	30·5	Dougill, Hodsman, and Cobb, 1915.
1% Fe_2O_3 : 1% Alk } 1330° C.	1000	40·5	
53% SiO_2 : 43% Al_2O_3	100	16·9	Boyd Dudley, 1915.
2% Fe_2O_3 : 1·5% Alk	1000	33·9	

§ (28) ELECTRICAL RESISTANCE.[2]—

Temperature.	Ohms per sq. cm. per cm. thickness.
600°	21000
700°	17000
800°	13000
900°	9000
1000°	6600
1100°	4400
1200°	2300
1300°	1300
1400°	690
1500°	280
1550°	60

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IV. SILICEOUS REFRACTORIES

§ (29).—Under this heading we include all materials containing more than 90 per cent of SiO_2. Although the normal refractoriness of siliceous refractories does not exceed that of Grade I. fireclays, nevertheless silica is used largely in all industrial operations where the temperatures exceed those at which firebricks begin to soften under working conditions. A silica brick is composed of a crystalline silica skeleton which has a comparatively sharp melting-point and, therefore, will withstand working temperatures near to its normal softening-point.

§ (30) PROPERTIES OF PURE SILICA.—Silica (SiO_2) can exist either as an amorphous material or in a number of crystalline forms: α and β quartz, α, β_1, β_2 tridymite, and α and β cristobalite. α quartz is the stable phase at low temperatures up to 575° C., where inversion to β quartz occurs. β quartz is stable between 575° and 870° C. From 870° C. to 1470° C. β tridymite is the stable phase, and above 1470° cristobalite. The melting-point of cristobalite is 1710° C.[3] and that of tridymite 1670°. Each of the three forms, however, may exist over a large range of temperatures. It is characteristic of silica that the inversions quartz $\leftrightharpoons$ cristobalite, quartz $\leftrightharpoons$ tridymite, and cristobalite $\leftrightharpoons$ tridymite are extremely slow, as is also the rate of crystallisation of the amorphous material. We find, therefore, that the metastable phases may persist for indefinite periods at temperatures far removed from their ranges of stability. We may thus find amorphous silica, quartz, tridymite, and cristobalite all together in a block which has been kept at one temperature for years. The inversions $\alpha \leftrightharpoons \beta$ quartz, $\alpha \leftrightharpoons \beta_1 \leftrightharpoons \beta_2$ tridymite, $\alpha \leftrightharpoons \beta$ cristobalite take place rapidly, and we thus find in silica the curious anomaly that the rapid inversion of one metastable phase to another may be repeated backwards and forwards without the appearance of the crystalline phase which is stable at that temperature.[4]

The temperatures of the rapid inversions are:

$\alpha \leftrightharpoons \beta_1$	Tridymite . . .	117° C.
$\beta_1 \leftrightharpoons \beta_2$	Tridymite . . .	163° C.
$\alpha \leftrightharpoons \beta$	Quartz	575° C.
$\alpha \leftrightharpoons \beta$	Cristobalite . . .	200°-270° C.

(depending on the previous history of silica).

If either quartz or amorphous silica is heated to, say, 1400° C., cristobalite is at first formed, and it is only after very prolonged heating that inversion to tridymite—the stable phase at that temperature—occurs. In the presence of a suitable flux, however, the inversions take place rapidly. Amorphous silica is serviceable for use as a refractory at temperatures up to 1000° C. for prolonged periods without crystallisation (in the absence of fluxes). But

[1] See Vol. I., "Heat, Conductivity of," § (4), Table II.
[2] Stansfield, Macleod, and McMahon, *Trans. Am. Electrochem. Soc.*, 1912, xxii. 89.
[3] Ferguson and Merwin, "The Melting Points and Cristobalite and Tridymite," *Amer. Jour. Sci.*, Aug. 1918, vol. xlvi.
[4] Fused silica tends to devitrify if heated and cooled a number of times through the inversion points $\alpha \leftrightharpoons \beta$ cristobalite.

crystallisation proceeds at 1200° C. Owing to its exceptionally high thermal endurance (due to its low coefficient of expansion) amorphous silica vessels are of great use in the laboratory. Tubes of this material can be plunged while red-hot into water without fear of fracture. Unfortunately the high cost of manufacture of fused silica ware limits its uses for industrial purposes.

§ (31) Specific Gravity. — The specific gravity of α quartz is 2·650, that of α tridymite and α cristobalite being 2·270 and 2·333 respectively. The specific gravity of fused amorphous silica is 2·21. There is, therefore, a considerable volume change accompanying the inversion of quartz to cristobalite or tridymite; this amounts to about 16 per cent (volume). The changes in linear dimensions associated with the inversions of the α and β forms of the crystalline phases are as follows:

$\alpha \leftrightharpoons \beta$	Cristobalite (220°-270° C.).	1 per cent.
$\alpha \leftrightharpoons \beta$	Tridymite (117° C.) . .	0·15 per cent.
$\alpha \leftrightharpoons \beta$	Quartz (575° C.) . .	0·45 per cent.

§ (32) Identification.—The various crystalline constituents may be identified in a mixture by the microscopical examination of the optical properties of the powdered material. The most convenient procedure is to immerse the powder in a liquid of standard refractive index and to determine the refractive index of the powder by the Becke line method.[1]

The optical constants are as follows:

Fused silica:	refractive index 1·4585.
Quartz:	refractive index ω 1·544, ε 1·553; double refraction ·009.
Tridymite:	refractive index α and β 1·469, γ 1·473; double refraction ·004.
Cristobalite:	refractive index 1·486; double refraction ·003.

By choosing a liquid of refractive index 1·480, the tridymite and cristobalite can be distinguished (potassium mercuric iodide is suitable. The solution is unstable and requires to be kept stoppered and checked repeatedly.) In the hands of a skilled worker the quantities of the various constituents can be estimated under the microscope to within 1 per cent.

§ (33) Coefficient of Expansion.—The coefficient of amorphous silica is

0°-30°	$\cdot 42 \times 10^{-6}$
30°-100°	·53
100°-500°	·58
500°-900°	·50
900°-1100°	·80

Fig. 6 gives the expansions of the quartz, tridymite, and cristobalite. The mean coefficients of expansion from 15° to 1000° are approximately

Quartz	$13{\cdot}5 \times 10^{-6}$
Tridymite	$9{\cdot}2 \times 10^{-6}$
Cristobalite	$15{\cdot}3 \times 10^{-6}$

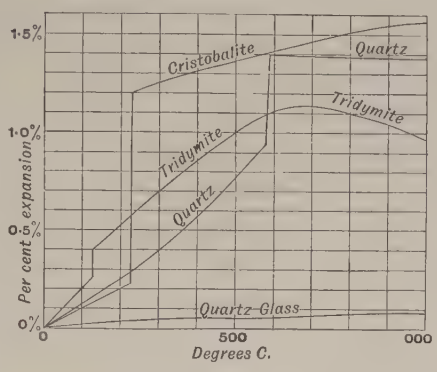

Fig. 6.

§ (34) Specific Heats.[2]—

	Amorphous.	Quartz.	Cristobalite.
0°-100°	·1845	·1869	·1883
0°-300°	·2124	·2168	·2334
0°-500°	·2302	·2380	·2426
0°-550°	..	·2439	..
0°-600°	..	·2500	..
0°-700°	·2422	·2543	·2509
0°-900°	·2511	·2596	·2569
0°-1100°	..	·2641	·2625
0°-1300°	..	..	·2662
0°-1400°	..	..	·2680

§ (35) Silica Bricks —Commercial silica bricks contain from 90 to 97 per cent SiO_2, the average good-quality brick containing 95 to 97 per cent. The siliceous rocks selected for manufacture, quartzites, sandstone, millstone grits, ganister, are composed of 95 to 99 per cent quartz, together with various impurities, *e.g.* clay, iron, lime, magnesia, etc. The presence of a basic material which will flux with the silica is essential to ensure the conversion of the quartz to tridymite or cristobalite at a reasonable firing temperature in as short a time as practicable. An excess of flux, such as lime, is not permissible, since the refractoriness of silica, particularly the refractoriness under load, falls rapidly with small additions of impurities (§§ (19) and (44)).

The form in which the impurities occur is of importance, since it is desirable that the fluxes should be finely disseminated throughout the whole mass to ensure rapid fluxing. In selecting a rock for the manufacture of silica bricks, tests are usually made to estimate the rapidity of conversion of the quartz, and it is this factor, as much as the chemical composi-

[1] Described in text-books on Petrology, *e.g.* Johannsen's *Manual of Petrographic Methods.* See "Immersion Refractometry," Vol. IV.

[2] White, *Am. Jour. Sci.*, Jan. 1919, vol. xlvii.

tion, which determines the suitability of the rock for the purpose. In a few cases rocks are found from which bricks and blocks can be made without the addition of a bonding material; for example, some forms of ganister are suitable; but in general it is necessary to add some bond, lime being the most popular. An important point in the selection of silica rocks is that on crushing they should yield angular grains.

The following are typical analyses of siliceous rocks used for brick manufacture:

SiO_2 . . .	97·6	98·1	97·0	97·2	96·7
Al_2O_3 . . .	0·7	0·4	0·4	1·0	1·59
Fe_2O_3 . . .	0·4	0·4	0·3	1·0	0·43
TiO_2 . . .	0·4	0·3	0·2	..	..
CaO . . .	0·02	0·1	0·05	0·1	0·07
MgO . . .	0·03	0·03	0·2	0·25	..
Na_2O and K_2O .	0·3	0·2	0·3	..	0·21

The refractoriness of these rocks is about Cone 35 (1770° C.).

In the process of manufacture the rocks are first crushed to lumps 1 in. to 2 in. in diameter and subsequently ground in an edge runner mill and screened into several grades, the coarsest grade used being $\frac{1}{8}$ in. to $\frac{1}{4}$ in. The desired proportions of the various grades are then selected to yield as dense a packing as possible. A proportion of fine dust is included, and this, in addition to producing a dense body, increases the surface factor and hence the rate of reaction and conversion of the quartz during the firing. If lime be added as a bond (which is usual) it is generally introduced as milk of lime, about 3 per cent or less according to the purity of the raw materials. The mixture is then watered and tempered for a short time in a light edge runner mill—a quarter of an hour is usual—and it is then ready for working.

Silica bricks may be moulded by hand, by a lever hand-press, or in machines by hydraulic pressure. The hand-moulding process is carried out in iron moulds—sometimes lubricated with oil—the mixtures being heavily tamped in by hand. The wear on the moulds is severe (also on the hands of the operators, who are compelled to wear gloves), due to the corroding action of the lime.

The bricks pressed by hand in a lever press are not on the whole so satisfactory as the hand-moulded, since they have not the uniformity of the hand-moulded brick, while they do not possess the compensating advantage of the high density produced in the hydraulic presses. However, the output per man is larger than with the moulded bricks, and the process is in operation in many works.

Machine-made bricks are formed under great pressure—up to 150 tons per brick. It is difficult to secure an even distribution of pressure over the whole surface of the brick, but when this is successfully done the brick produced is in most respects superior to the hand-made brick. It is more true to specified dimensions and has a denser structure; the surface of the brick is of a finer texture, the fine grains being carried to the surface with the water which is pressed out of the brick. In consequence, these bricks are better able to resist the corrosive action of slags and flue dust. Owing chiefly to faulty technique in the early days of the pressed brick industry there is a prejudice against machine-made bricks. If the pressure is uneven the bricks are liable to spall. Comparative experiments carried out on machine- and hand-made bricks made and fired under similar conditions, show that the crushing strength of the machine brick is 25 per cent greater than the hand-made, and the resistance to abrasion is also greater. Further, the machine-made brick, though denser, gave the better results when tested for deterioration of strength due to sudden changes of temperature.

The bricks are friable when damp, but set sufficiently hard for handling when dry. They are dried rapidly, since there is no drying shrinkage.

When dry they are set in the burning kiln, due allowance being made for expansion on firing.

Single down-draught kilns are the type preferred for firing silica bricks. The firing may be carried out much more rapidly than with fireclay articles, especially in the early stages. During the firing the α quartz is converted into β quartz, is subsequently converted into cristobalite, and finally into tridymite. The true increase in volume is from 13 to 16 per cent. On firing there is usually an increase in porosity due to the rearrangement of the crystals, and the expansion of the brick, if hard-fired, in consequence, generally exceeds 20 per cent (by volume). The finishing temperature in a well-fired refractory brick is from Cone 15 to 20 (1435° C. to 1530° C.). Some bricks are only fired to Cone 14 (1410° C.) or even Cone 12 (1350° C.). In these latter the percentage of unconverted quartz is inordinately high.

Great care has to be exercised in the cooling of the kilns after firing—particularly in passing through the α β transformation temperatures.

§ (36) Properties of Silica Bricks.—

Composition.	Typical Analyses.		
SiO_2	96	96	94·2
CaO	3	1·5	2·2
Al_2O_3 . . .	0·5	1·0	1·6
Fe_2O_3 . . .	0·3	0·8	1·6
MgO	0·2	0·3	0·1
Alkalis . . .	..	0·4	..

The unconverted quartz varies between 25 and 70 per cent. Scott gives the following

figures for average samples of commercial bricks :

English :	Unconverted quartz	36-52%	Aver. 45%
German :	„ „	41-49%	„ 44%
American :	„ „	22-28%	„ 25%

In the hard-fired bricks tridymite is the principal constituent. With lower firing temperatures and higher quartz contents more cristobalite is found.

Porosity.—20 to 30 per cent.

Strength.—A good brick should have a clear ring. The crushing strength varies from 1600 lbs. per sq. in. to 10,000 lbs. per sq. in. (tested on the flat).

Specific Gravity.—The specific gravity depends on the amount of unconverted quartz. In commercial bricks it lies between 2·3 and 2·5. In a well-fired brick the specific gravity should not exceed 2·38, or at most 2·4.

Refractoriness.—Good bricks should not squat below Cone 32 to Cone 34 (1710° C. to 1750° C.). Some bricks which give reasonable service, however, have a refractoriness as low as Cone 30 (1670° C.). Bricks having a refractoriness below Cone 29 (1650° C.) offer little advantage over high-grade fireclay bricks.

Refractoriness under Load.—The refractoriness of silica under load does not deteriorate to the same extent as that of fireclays. With high-grade silica bricks of refractoriness of Cone 33 (1730° C.) or higher, the refractoriness under load (50 lbs.) varies from Cone 30 to Cone 17 (1670° C. to 1480° C.), according to the fineness of the texture. A very coarse texture shows practically no deterioration under load, but an excessively fine texture may behave similarly to fireclays. A brick of Cone 30 and under may fail under load, particularly if fine-grained.

Coefficient of Expansion.—The expansion is governed by the amount of cristobalite and tridymite present in the brick (for their expansions see § (33)). The following are the coefficients of expansion of two samples of silica bricks :

A. Moderate firing	Sp. gr. 2·40
B. Harder firing	Sp. gr. 2·35

Neither brick contained tridymite in appreciable quantities.[1]

	"A."	"B."
15°-1000°	$11·8 \times 10^{-6}$	$10·7 \times 10^{-6}$
15°-250°	$30·4 \times 10^{-6}$	$28·0 \times 10^{-6}$
250°-500°	$10·1 \times 10^{-6}$	$8·4 \times 10^{-6}$
500°-600°	$12·7 \times 10^{-6}$	$6·1 \times 10^{-6}$
600°-1000°	$1·7 \times 10^{-6}$	$3·1 \times 10^{-6}$

Specific Heats.—The specific heats do not differ greatly from firebricks. Bradshaw and Emery give values for a silica brick of the following composition :

SiO_2	96·6
Al_2O_3	1·2
CaO	1·02
Fe_2O_3	0·75

Temperature Range.	Mean Sp. Ht.
25°-600°	·226
25°-1000°	·263
25°-1200°	·282
25°-1400°	·293

Value for a silica brick by Heyn, Bauer, and Wetzel (see "Specific Heat of Clay").

Temperature Range.	Mean Sp. Ht.
20°- 200°	·220
20°- 400°	·238
20°- 600°	·252
20°- 800°	·260
20°-1000°	·263
20°-1200°	·267

CONDUCTIVITY (THERMAL)[2]

	Temperature ° C.	$K \times 10^4$ C.G.S. Units.	Authority.
Silica Bricks—			
94% SiO_2 : 1% Al_2O_3 (burnt at) 2% Fe_2O_3 : 2·0% CaO (1050° C.)	100-1000	20·0	Wologdine, 1909.
	150-930		
Ditto . (burnt at 1300° C.)	150-930	31·0	Wologdine, 1909.
95% SiO_2 : 2% Al_2O_3 1·1% Fe_2O_3 : 1·5% CaO	400-1200	36·0	Dougill, Hodsman, and Cobb, 1915.
96% SiO_2 : 0·9% Al_2O_3 0·8% Fe_2O_3 : 1·8% CaO	100	22·0	Boyd Dudley, 1915.
	1000	42·5	Boyd Dudley, 1915.

ELECTRICAL RESISTANCE[3]

	Ohms per cub. cm.
1300°	9700
1400°	2400
1500°	710
1550°	22
1565°	18

[1] Houldsworth and Cobb, *Trans. Cer. Soc.* xxi. 227.

[2] See Vol. I. "Heat, Conduction of." § (4), Table II.

[3] Transfield, Macleod, and McMahon, "Electrical Resistivity of Firebricks at High Temperatures," *Trans. Am. Electrochem. Soc.*, 1912, xxii. 89.

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V. PORCELAIN

§ (37).—The refractory porcelains consist essentially of mixtures of alumina, quartz, and alkalis, fired to a temperature sufficiently high, usually about 1450° C., to produce a vitreous body having a glassy matrix in which the quartz is partly or entirely dissolved and crystalline sillimanite is formed. The raw materials used in the manufacture are china clay, felspar, and finely ground silica, with the occasional addition of lime, alumina, or magnesia. The amount of felspar present varies from 10 to 25 per cent in the average hard porcelains, and the china clay from 40 to 55 per cent. The refractoriness is increased by further additions of china clay; in the hardest porcelains calcined alumina is added. The following are approximate compositions based on analytical results:

	China Clay.	+ Mica.	Silica.	Felspar.	Alumina.	
A. French porcelain . .	41	4	24	31	..	·4 RO . R_2O_3 5 SiO_2.
B. Berlin „ . .	49	6·3	24·3	20·5	..	·25 RO . R_2O_3 4·4 SiO_2.
C. Japanese „ . .	33	9·6	42·6	14·7	..	·4 RO . R_2O_3 6 SiO_2.
D. Marquart „ . .	72	...	..	..	28	Al_2O_3, SiO_2

The raw materials are either weighed dry and then ground together in a cylinder, or ground separately in water and mixed by volume, knowing the dry weights per volume of slip. The body is formed by (i.) "throwing" on a potter's wheel, (ii.) pressing by hand in plaster moulds, (iii.) pressing as a damp powder in steel dies, (iv.) slip casting, (v.) extrusion.

The ware is lightly fired to a temperature not usually exceeding 800° C., and is then sufficiently strong to be handled with safety. It is then dipped in the glaze which is prepared in the form of a slip, and finally fired to a high temperature—from 1350° to 1500° C. The glaze is a mixture of china clay, flint (quartz), and felspar, to which lime is usually added, the constituents being water-ground to a very fine state of division. For the above porcelain mixtures appropriate glazes would have the following approximate composition:

	RO.	R_2O_3.	SiO_2.
A . . .	1·0	1·24	10·84
B . . .	1·0	1·00	8·91
C . . .	1·0	0·55	5·0
D . . .	1·0 (CaO)	1·0	1·0

It is necessary to adjust the composition of the glaze so that the coefficient of expansion may be the same as that of the body, in order to avoid excessive strain in cooling. The coefficient of expansion can be calculated roughly from the formula E (linear coefficient of expansion) $= \Sigma pk/100$, p being the percentage of oxide in the glaze and k a constant assigned to the oxide. Values for k are (approximate):

SiO_2 . . .	0·26
Al_2O_3 . . .	1·0
CaO . . .	1·6
Na_2O . . .	3·3
K_2O . . .	2·9

It will be seen, therefore, that an increase in the silica lowers the coefficient of expansion of the glaze. These constants are only applicable to a vitreous material.

The glaze, in addition to the desired coefficient of expansion, must "mature" at the temperature of firing, that is to say, must present a highly glossy appearance, free from pin-holes, blisters, and matt surfaces. Underfiring or overfiring both destroy the appearance of the glaze. For any particular maturing temperature there is a considerable range of variation in the silica content permissible (keeping the RO/R_2O_3 ratio constant), and this range increases with the maturing temperature. Keeping the silica/RO constant the permissible variation of the Al_2O_3 content is much smaller.

Careful cooling is necessary to avoid strain even in porcelain where the expansions of the body and glaze are well matched.

§ (38) CONSTITUTION OF PORCELAIN BODY.—The following changes take place during the firing. At about 1200° the felspar fuses to a glass, but from that temperature up to 1300° C. the viscosity of the glass is too high to permit of a rapid process of solution. The dissociated clay appears to form amorphous sillimanite,

and the residual silica from the decomposition of the clay dissolves in the glass. As the temperature is raised the amorphous sillimanite $Al_2O_3\ SiO_2$ begins to crystallise, needle-shaped crystals (refractive index 1·64) appearing.

At the same time the quartz begins to dissolve. At 1310° small crops of sillimanite crystals can be seen, but the solution of quartz is not appreciable, the grains still having a sharply angular outline. At 1340° about 5 per cent of the quartz is dissolved, the grains becoming slightly rounded at the edges, and the ratio of crystalline to amorphous sillimanite is increased. At 1400° C. the quartz grains are badly corroded. If the Al_2O_3 content of the body is high, crystals of sillimanite will be abundant. Firing above 1400° will complete the crystallisation of the sillimanite, and at 1450° most of the quartz will have been completely dissolved. The temperatures given above are for the average hard porcelain. For a porcelain with a higher felspar content and containing lime, the temperature at which the solution of the quartz and the crystallisation of the sillimanite takes place will be considerably lower. Since the viscosity of the glassy matrix falls rapidly with a small increase in temperature, it follows that a small rise in the temperature will, over certain temperature ranges, produce more change in the structure than a prolonged firing at a lower temperature. It is possible, therefore, with a knowledge of the composition of the body to estimate by microscopic examination the temperature to which the body has been fired—if the firing temperature is low. The relative influence of time, however, is more pronounced with a high firing, since the variation of the rate of diffusion with temperature is less, and it is possible to produce the same structure with a prolonged firing as with a short firing at a slightly higher temperature.

The addition of lime and magnesia modifies the properties of porcelain. MgO imparts a long vitrifying range to the body, a high thermal conductivity, low coefficient of expansion and, in consequence, a high thermal endurance.

§ (39) Properties of Porcelain.—

Normal Refractoriness.—Cone 30.

Crushing Strength.—About 65 tons per sq. in.

Specific Gravity.—2·2 to 2·5.

Coefficient of Expansion.—(0°-100°)

1·5 to $3{\cdot}4 \times 10^{-6}$.

Berlin .	$1{\cdot}77 \times 10^{-6}$	(16° to 191°)
	$3{\cdot}36 \times 10^{-6}$	(16° to 250°)
	$3{\cdot}66 \times 10^{-6}$	(16° to 500°)
	$4{\cdot}34 \times 10^{-6}$	(16° to 1000°)
Meissen .	$2{\cdot}69 \times 10^{-6}$	(0° to 100°)
Bayeux .	$2{\cdot}52 \times 10^{-6}$	0°
	$3{\cdot}27 \times 10^{-6}$	50°
	$4{\cdot}01 \times 10^{-6}$	100°
	$4{\cdot}31 \times 10^{-6}$	120°
Rosenthal .	$3{\cdot}52 \times 10^{-6}$	0° to 100°
Seger . .	$3{\cdot}8 \times 10^{-6}$	20° to 100°

The coefficient of expansion is largely influenced by the firing, inasmuch as crystalline quartz imparts a high coefficient, whereas quartz in solution gives a low value. Thus a hard-fired porcelain rich in quartz will have an expansion appreciably lower than a lightly fired porcelain.

Specific Heat.—15°-1000° ·255.

Berlin . { ·202 (20°-200°) ; ·221 (200°-400°)

Conductivity (Thermal).—·0025.

Conductivity (Electrical).—(C.G.S. units.)

$·25 \times 10^{-12}$	97·5° C.[1]
$·26 \times 10^{-11}$	189° C.[1]
$·05 \times 10^{-6}$	400° C.[2]
$·1 \times 10^{-6}$	1000° C.[2]

Dielectric Constant.—4·4 to 6·8.

VI. Carbonaceous Refractories

§ (40).—The use of carbon as a refractory is principally confined to the manufacturers of graphite crucibles for melting steel, brass, aluminium, and other alloys.

Natural Sources.—The principal sources are Ceylon and Madagascar. The following are typical analyses of Madagascar graphite :

Carbon	84·32	87·16
Fe_2O_3	1·04	0·88
SiO_2	7·10	5·56
Al_2O_3	5·66	4·13
MgO	0·09	0·12

The Ceylon variety contains as a rule more carbon, and the ash, although less in quantity than that in the Madagascar graphite, is more siliceous and ferruginous and therefore more fusible.

In selecting a graphite for crucible-making the composition of the ash is of importance, since the resistance to oxidation is largely determined by the protective glaze formed round the grains, and this is derived from the clay bond (and other fluxes added for the purposes) and from the interaction of the ash with the bond. Iron is particularly objectionable as an impurity. Of greater importance are the physical properties, the grading, density and texture of the flakes. Since the conductivity and other properties may vary 100 per cent or more with the orientation of the grains, it is necessary to select mixtures which will enable the orientation to be controlled as far as possible.

Flake graphite, such as Madagascar, is the most suitable ingredient for crucible-making, although it is usually necessary to add to it a small proportion of a graphite, such as the Ceylon graphite, which requires grinding.

[1] Dietrich, *Physikal. Zeit.*, 1910, p. 187.
[2] Goodwin and Mailey, *Phys. Rev.*, 1908, p. 322.

From 30 to 40 per cent of a plastic bond clay is employed. Popular clays for the purpose have been the Klingenberg and the Gross Almerode (for analyses of these clays see § (19)), the normal refractoriness being Cones 30 and 28 (1670° C. and 1630° C.) respectively. To increase the refractoriness it is usual to add china clay. Sand (5 to 8 per cent) and grog (anything up to 20 per cent) are added to reduce the firing shrinkage.

The crucibles are usually made in some form of a potter's jolley, the mixture being thrown into an iron mould and the crucible shaped internally with a suitable former as the mould is rotated. It is essential that the graphite flakes should be correctly orientated. The strength, thermal conductivity, and other properties are different according as measurements are made parallel to the plane of the flakes or perpendicular. When the clay is made to flow under pressure, the flakes assume a direction with their planes parallel to the line of flow. Various ingenious processes are used to ensure that the grain in a crucible shall run radially or tangentially according to the purpose for which the crucible is made; the bottom, particularly at the corner, presents special difficulties. The conductivity and tensile strength are greatest in a direction parallel to the grain, hence, for thermal efficiency, the flakes should run radially. Such a crucible, however, would be weak if lifted by tongs from the furnace, the tension under the weight of the metal in the crucible being perpendicular to the grain.

In practice special types are made for different methods of use and handling.

The firing is sometimes carried out under oxidising conditions, in which case the temperature of firing does not exceed 700° C. Alternatively, the firing may be carried out in a muffle kiln at temperatures up to 1000° C. Another method is to pack the "green" articles in saggars containing carbonaceous dust. Under these circumstances, the firing temperature is raised to 1250° C. without fear of oxidation. The firing temperature required depends on the use for which the mixing is intended. If a crucible is to give reasonable service, it is necessary that a portion of the bond be fused to form a protective glaze for the graphite grains. If the crucible is manufactured for steel-melting, the high temperature in the melting furnace will rapidly and effectually glaze the crucible. For this purpose, therefore, a high firing temperature is not necessary to secure protection from oxidation; it is, therefore, avoided, since the higher the firing temperature the greater the risk of oxidation and cracking during firing. For brass-melting it is possible to choose a bond which will give the required glaze at the working temperature of the furnace, and in this case also, therefore, a high firing temperature is not essential. For low temperature work, such as the melting of aluminium alloys, a dense body is required, since the low furnace temperature is sufficiently high to oxidise any unglazed graphite at an appreciable rate, but is not high enough to develop a good glaze. A dense mixture is, therefore, chosen for these pots. The shrinkage in firing is small, perhaps 1 to 2 per cent in the plane of the flakes, and 5 to 6 per cent perpendicular to the plane. Excessive shrinkage in the latter direction is prevented by the sand and grog. The life of a crucible in a steel furnace is about six heats. In brass-founding a good crucible should last for about forty heats.

§ (41) Properties of Graphite Refractories.—

Specific Gravity.—2·25 to 2·26.

Tensile Strength.—200 to 500 lbs. per sq. in.

Coefficient of Expansion.—

$7{\cdot}86 \times 10^{-6}$ at 40° C.
$7{\cdot}91 \times 10^{-6}$ at 50° C.

Specific Heat.[1]—

10° C. . . .	·160
61·3 . . .	·199
138 . . .	·252
202 . . .	·297
249 . . .	·325
622 . . .	·445
822 . . .	·454
977 . . .	·467

Conductivity (Thermal).—·0141.

Electrical Resistance. — Specific resistance ·003.

In bonded graphite crucibles the properties vary greatly with the orientation of the grains; thus the thermal conductivity may be 100 per cent greater parallel to the grains than at right angles to them.

VII. The Refractory Oxides

§ (42).—The pure refractory oxides, although debarred, on the grounds of cost, from use on a large scale in industrial operations, are important in the laboratory in connection with the preparation of pure samples of the refractory metals for research purposes. The growth of research on the physical constants and chemical reactions and equilibria at extreme temperatures has created a demand for special refractories which cannot be met by the manufacturers of refractories in the ordinary way since the requirements are usually unique for any particular research and the quantities involved are small. With a knowledge of the properties of these special refrac-

[1] Mean values over a small temperature range. The specific heat approaches a maximum at about 1000° C.

tories and their behaviour at high temperatures the manufacture of small articles, such as tubes, crucibles, and so on, in the laboratory is an easy matter, and well worth the undertaking where it is part of the routine of the laboratory to carry out research on the physical constants and constitutional diagrams of alloy systems at high temperatures.

The oxides important for refractory purposes are MgO, ZrO_2, CaO, Al_2O_3, and SiO_2. The melting-points and approximate boiling-points are :

	Melting-point.	Boiling-point.
MgO	2800°	3600°
ZrO_2	2700°	4300°
CaO	2570°	3400°
Al_2O_3	2050°	3800°
SiO_2	1670°-1710°	3500°

Other refractory oxides are those of :

	Melting-point.	Boiling-point.
Beryllium	2410°	2900°
Yttrium	2350°	4300°
Thorium	2450°	4400°

The figures for the boiling-points are taken from Mott.[1]

With the exception of MgO these oxides are readily reduced at high temperatures, and for many purposes MgO, on the score of refractoriness, is the most satisfactory if the basic character of this oxide is not objectionable. If, for example, a metal is to be melted under an acid slag, MgO would be corroded. It appears to volatilise, however, at temperatures near its melting-point, but at lower temperatures undergoes little change. Silica, and to a smaller extent, alumina, emit dense fumes at temperatures which, under certain circumstances, may be as low as 1600° C. It seems probable that a volatile product of reduction may be formed under strongly reducing conditions, subsequent conversion to the oxide and condensation taking place under suitable conditions. In the case of Al_2O_3 metallic aluminium (B.P. 1800° C.) may be volatilised. (See also § (46) for MgO.)

§ (43) The Manufacture of Crucibles for Laboratory Work.—It is essential that all the oxides when used for making refractory crucibles, etc., should be in the dead-burnt or fused condition. The easiest procedure is to fuse the oxide by passing an electric current through it in the manner described elsewhere.[2] The oxides all begin to conduct at temperatures well below their melting-points. For example, the following table shows the resistance of fused magnesia :[3]

Temperature.	Specific Resistance. Ohms.
1060°	420,000
1100°	320,000
1170°	62,000
1230°	24,000
1352°	510
1386°	415

The fused oxide is ground finely in an iron mill, the iron removed first magnetically, and finally by treatment with acid, or by passing phosgene gas over the oxide heated to 300°. This latter process removes the last trace of iron. The powder is then moulded to the desired form. Sufficient plasticity can be obtained by mixing a little gum tragacanth with the oxide. It is sometimes found useful to use as a binder a small quantity—5 to 10 per cent—of the unfused oxide. The articles are then fired in a suitable electric furnace (see "Furnaces for Laboratory Use").

A mixture of oxides will frit together if heated to temperatures far below the melting-points of either, and, in this way, excellent crucibles can be made when the extreme refractoriness of the pure oxides is not required. Spinel (MgO, Al_2O_3) offers great advantages for this purpose.

§ (44) Binary and Ternary Systems.—The constitutional diagrams of binary mixtures of Al_2O_3, CaO, MgO, SiO_2, have been studied at the Geophysical Laboratory, U.S.A., also the ternary systems, MgO Al_2O_3 SiO_2, CaO Al_2O_3 MgO, CaO MgO SiO_2. *Figs.* 7-12 show the six binary systems.

Fig. 7 shows the liquidus of the CaO MgO system.

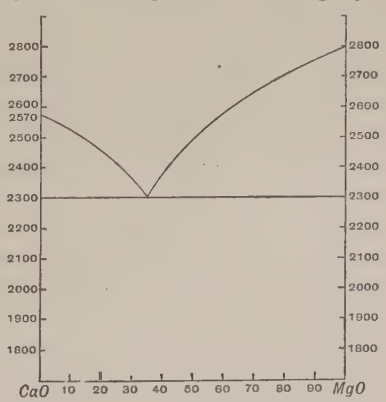

Fig. 7.

No compounds are formed. The eutectic composition is CaO 67 per cent, MgO 33 per cent. Melting-point 2300°.

[1] *Trans. Amer. Electrochem. Soc.*, 1918, xxxiv. 255.

[2] See "Furnaces for Laboratory Use."

[3] Northrup, *Trans. Amer. Electrochem. Soc.*, 1918, xxxiii. 215.

It will be observed that all the binary and ternary compounds found consist of simple molecular ratios of the oxides.

Some eutectics in the ternary systems are :

				Melting-point.
CaO 30·6%	MgO 8%	SiO_2	61·4%.	1320°.
CaO 36%	MgO 12·6%	SiO_2	51·4%.	1350°.
CaO 29·8%	MgO 20·2%	SiO_2	50%.	1357°.
CaO 46%	MgO 6·3%	Al_2O_3	47·7%.	1347°.
CaO 41·5%	MgO 6·7%	Al_2O_3	51·8%.	1345°.

Fig. 8 is the MgO Al_2O_3 system. One compound is found, MgO Al_2O_3 (MgO 28·4%, Al_2O_3 71·6%). Melting-point 2135°.

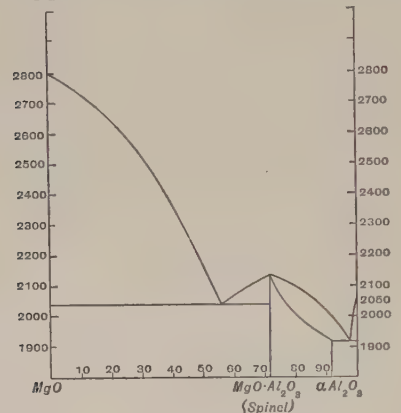

FIG. 8.

Eutectics :

MgO 45%. Melting-point 2030°.
MgO 8%. „ „ 2030°.

Fig. 9 is the SiO_2 MgO system.

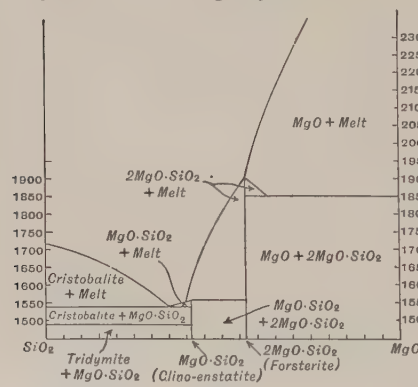

FIG. 9.

Compounds :

2 MgO SiO_2 (SiO_2 42·9%, MgO 57·1%).
Melting-point 1890°. (Forsterite.)
MgO SiO_2 (unstable)—Melting-point 1560°.

Eutectics :

SiO_2 37%. Melting-point 1850°.
SiO_2 65%. „ „ 1543°.

Fig. 10 is the CaO Al_2O_3 system.

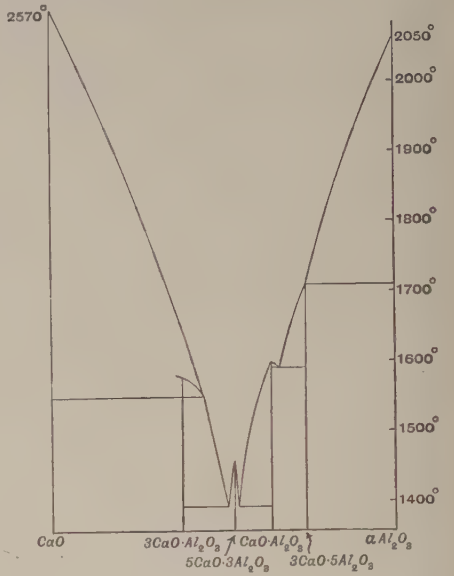

FIG. 10.

Compounds :

3CaO Al_2O_3 (CaO 62·22%) (unstable).
Melting-point 1535°.
5CaO $3Al_2O_3$ (CaO 47·78%).
Melting-point 1395°.
CaO Al_2O_3 (CaO 35·44%).
Melting-point 1600°.
3CaO $5Al_2O_3$ (CaO 24·78%).
Melting-point 1720°.

Reference should be made to the original papers, the study of which yields information as to the effect of the contamination of the pure oxides with other oxides, the choice of a suitable bond, and the fields in which highly refractory products are likely to occur.

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N. L. Bowen, "The Ternary System Diopsive—Forsterite Silica," *Am. Jour. Soc.*, 1914, xxxviii. 207.

Shepherd and Rankin, "Ternary System—CaO, Al_2O_3, SiO_2," *Jour. of Ind. and Eng. Chem.*, 1911, vol. iii. No. 4.

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Rankin and Merwin, "Ternary Systems—MgO, Al_2O_3, SiO_2," *Amer. Jour. Sci.*, 1918, April.

Rankin and Merwin, "Ternary Systems—CaO, Al_2O_3, MgO," *Jour. Am. Chem. Soc.*, 1916, March.

Andersen, "The System Anorthite—Forsterite Silica," *Am. Jour. Sci.*, 1915, April.

Fig. 11 is the $CaO\ SiO_2$ system.

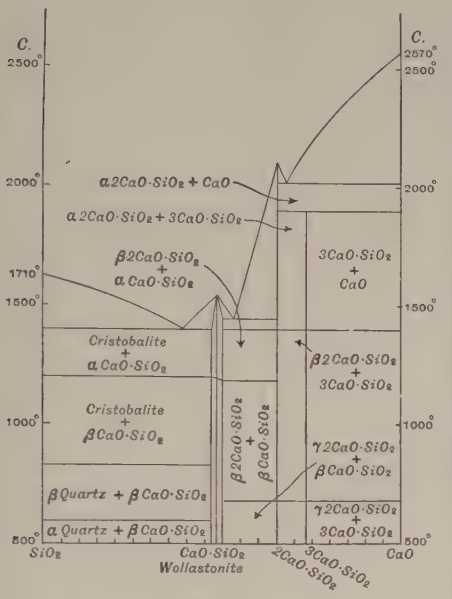

FIG. 11.

Compounds:

$CaO\ SiO_2$ (CaO 48·2%). Melting-point 1540°.
$2CaO\ SiO_2$ (CaO 65·2%). „ „ 2130°.

Eutectics:

CaO 67·5%. Melting-point 2065°.
CaO 54%. „ „ 1440°.
CaO 37%. „ „ 1426°.

Fig. 12 is the $Al_2O_3\ SiO_2$ system.

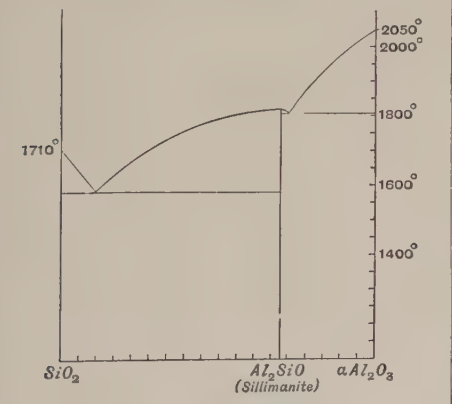

FIG. 12.

Compound:

$Al_2O_3\ SiO_2$ (Al_2O_3 62·9%). Melting-point 1816°.
(Sillimanite.)

Eutectics: Al_2O_3 64%. Melting-point 1810°.
Al_2O_3 7·4%. „ „ 1590°.

§ (45) MAGNESIA (MgO).—Magnesia is used extensively for furnace linings, particularly in the iron and steel industries.

"Magnesite" bricks are prepared from dead-burnt magnesite ($MgCO_3$). The principal sources of magnesite are Austria, Greece, India, and U.S.A. The two former are responsible for 90 per cent of the world's supplies. The following are analyses of raw and calcined magnesite.

AVERAGE ANALYSES

	Compact Magnesite (Greece, India, California).	Spathic Magnesite (Quebec, Norway, Worthington).	Spathic Breunnerite (Austria).
MgO	38-44	38-47	47
CaO	1- 3	0-10	0-2
Fe_2O_3 | Al_2O_3	2- 7	2	1
SiO_2	1- 5	1- 3	1-3
CO_2	50	49-51	50

TYPICAL ANALYSES OF THE CALCINED MAGNESITE

	Styrian (Austria).			Euboean (Greece).		Indian.
MgO	81·9	81·7	87·4	90·7	95·0	93·1
CaO	5·0	2·8	3·1	3·0	3·5	1·0
Fe_2O_3	..	7·4	8·3	0·7	0·13	1·2
Al_2O_3	11·35	0·6	..	0·7	0·9	..
SiO_2	1·75	7·6	1·2	4·2	0·2	4·4

The picked raw material is fired to a high temperature to convert it to the dead-burnt variety of high specific gravity. The temperature of calcining is in the neighbourhood of 1500° C. for the Styrian, and considerably higher for the Euboean. For some purposes lower grades of magnesite—rich in iron—are calcined to Cones 12-14 only. When calcined to Cones 12-14 the magnesia is in an apparently amorphous form, having a density of 3·2. With a higher calcining temperature crystallisation occurs, the density rising to 3·6-3·7 with the formation of periclase.

In the manufacture of bricks the dead-burnt magnesite is crushed and pulverised in a ball-mill or edge runner. The grading adopted is finer than that used in the manufacture of silica bricks—fractions coarser than $\frac{1}{8}$ in. being rejected. Generally, particles $\frac{1}{16}$ in. are selected as the largest size. The crushed material is moistened with water, tar or dextrin solution, etc., about 1 per cent being added, together with a bond if any is used. The choice of binding material is varied. The most usual is "caustic magnesia." This is made by calcining the raw magnesite to 700°-800°. About 10 per cent of this is added as a bonding material with or without magnesium chloride.

Iron oxide, clay, serpentine, borax, and other substances have also been used. The greater the quantity of bond, the easier the bricks are to mould, but the greater the shrinkage on firing. This limits the amount of bond permissible. The bricks may be moulded or pressed; pressing is the most usual, 3500-7000 lbs. per sq. in. being employed. The higher the temperature of firing, the better the brick produced. It is impossible to overfire. Poor-quality ferruginous bricks may be fired to Cone 12, but the better grades are fired to Cones 17-28, or even higher. Kilns are used similar to those employed in the silica industry.

§ (46) Properties of Magnesite Bricks.—In appearance these vary in colour from grey to a red brown. Some varieties are almost white or a light buff. Typical analyses:

	Euboean.	English.		Austrian.	
MgO .	93·4	85·4	82·4	88·2	80·8
CaO .	3·7	3·5	7·3	0·9	2·1
Fe_2O_3 .	0·5	4·5	1·96	7·1	5·9
Al_2O_3 .	0·2	2·1	1·29	0·9	4·1
SiO_2 .	2·8	4·4	6·8	2·4	8·0

These bricks are far superior to silica or fireclay in the presence of basic slag. They are readily fluxed by silica or alumina, but not apparently by magnetite. Successful furnaces have been constructed from iron boxes or tubes rammed with magnesite and placed as "headers" in the walls.

Magnesia appears to react with carbon and to volatilise, condensing on cooler parts of the flat):—Cold—1400-7000 lbs. per sq. in. Hot—the strength falls steadily with increasing temperatures and does not show any evidence of a discontinuity, such as is found in clay or siliceous refractories. Between 1300 and 1500 the strength falls off rapidly. Chatelier and Bogitch[1] give the following data for bricks of the composition shown:

	(1)	(2)	(3)	(4)
MgO . .	86·7	93·4	89·4	81·2
CaO . .	1·0	3·7	4·5	4·8
Fe_2O_3 . .	6·0	0·5	1·1	0·2
Al_2O_3 . .	0·6	0·2	0·8	1·0
SiO_2 . .	6·7	2·8	4·2	8·8

Crushing strength kg. per sq. cm. at

15°	145	420	390	230
1000°	85	320	..	..
1300°	66	280	..	..
1500°	3·6	185	90	16
1600°	1·8	8	4·8	3·5

Bodin gives the following figures for typical bricks from Styria and Euboea:

Crushing strength kg. per sq. cm. at

	20°	800°	1000°	1300°	1500°
Styria	450	295	190	155	30
Euboea	260	265	230	110	5

Refractoriness.—Normal refractoriness, Cones 40-42 (2000° C.). Under load (50 lbs. per sq. in.), Cone 18 (1500° C.).

Coefficient of Expansion.—The coefficient of expansion is the highest of all refractory materials, being (15°-1000°) $13{\cdot}5 \times 10^{-6}$ approximately. The expansion is uniform, the expansion-temperature curve being practically linear.

Specific Heat.—(0° – 100° C.) ·24.

Conductivity (Thermal)[2]

	Temperature °C.	$K' \times 10^4$ in C.G.S. Units.	Authority.
Magnesite Bricks—			
92% MgO : 5% SiO_2	320-560	151·0	Dougill, Hodsman, and Cobb, 1915.
1·6% Fe_2O_3 : 1·7% CaO	700-1400	91·0	
86·5% MgO : 2·5% SiO_2	450-830	135·0	Boyd Dudley, 1915.
7·0% Fe_2O_3 : 2·7% CaO			
Diatomite Bricks	100	3·10	National Physical Laboratory, 1916.
	500	4·61	

furnace. It is probable that the following reaction occurs:

$$MgO + C = Mg + CO$$
(Solid) (Solid) (Vapour) (Vapour).

The magnesia fluxes with fireclay at about 1550° C. and with silica at about 1610° C.

Specific Gravity.—3·4 (lightly fired), 3·6 (hard fired).

Porosity.—15-28 per cent. The best bricks have porosities 15-20 per cent.

Strength.—Crushing strength (tested on the

Electrical Resistance

	Specific Resistance. Ohms.
1300° C. . . .	6200
1400° C. . . .	420
1500° C. . . .	55
1550° C. . . .	30
1565° C. . . .	25

[1] Chatelier and Bogitch, "Sur les propriétés réfractaires de la magnésie," *Trans. Cer. Soc.* xvii. 181.

[2] See Vol. I., "Heat, Conduction of," § (4), Table II.

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Scott, "Microstructure of Magnesite Bricks," *Trans. Cer. Soc.* xvii. 475.
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McDowell and Howe, "Magnesite Refractories," *Jour. Amer. Cer. Soc.*, March 1920, p. 185 (with Bibliography).

§ (47) ZIRCONIA (ZrO_2). — The ores of zirconium occur abundantly in various parts of the world, Ceylon, N. and S. America, Urals, Norway, Australia. The most important deposits are in Brazil. Zirconia occurs as baddeleyite, the crude oxide, and zircon, the silicate ZrO_2, SiO_2—baddeleyite contains from 74 to 90 per cent ZrO_2—an average analysis is:

ZrO_2	82·0 per cent.
SiO_2	11·4 „ „
TiO_2	0·4 „ „
Al_2O_3	0·9 „ „
Fe_2O_3	3·1 „ „
Loss on ignition	2·0 „ „

Attempts have been made to manufacture bricks from the crude ore for industrial purposes, but, although it has been claimed that some satisfactory trials have been obtained, yet, on the whole, they have not been successful. The failure of ZrO_2 bricks is largely a fault in the manufacture. The behaviour of ZrO_2 on heating is similar to aluminous refractories, inasmuch as a steady shrinkage persists even after prolonged firing, and it is, therefore, necessary to use a high proportion of dead-burnt zirconia fired to temperatures equal to those employed in the calcination of magnesite for brick-making. Zirconia bricks, lightly fired and made from underfired grog, show a gradual deformation under load at comparatively low temperatures. For example, a sample of ZrO_2 brick, of normal refractoriness over Cone 40 (1920° C), may squat at 1400° under a load of 75 lbs. per sq. in.

Another portion of the same brick tested after firing it to 1650° may squat at 1730° under the same load, and a sample of the same material which has been fused in the electric furnace tested under similar conditions will squat at 1790°.

Bodin gives the strength of crude zirconia blocks at various temperatures:

Crushing strengths (kg. per cm.²)	20°	800°	1000°	1300°	1500°
	395	275	345	90	10

It will be seen that zirconia has a point of maximum strength at about 1100° similar to clay and siliceous refractories.

§ (48) PURE ZrO_2.—The complete purification on a commercial scale at a reasonable cost is difficult. Supplies are now obtainable, however (over 99 per cent ZrO_2), for laboratory purposes. Having regard only to the refractoriness of ZrO_2 the removal of silica is not necessary. The softening-point of the compound ZrO_2 SiO_2 (zircon)—containing 33 per cent of silica—is 2550°, and the eutectic between ZrO_2 and ZrO_2 SiO_2 melts at about 2300°. On the silica side of the compound the liquidus falls rapidly. We can therefore dilute the ZrO_2 with up to 33 per cent of silica without seriously decreasing the refractoriness.[1] The presence of iron greatly affects the refractoriness. Treatment with HCl removes most of the iron, and the ZrO_2 thus obtained is sufficiently refractory for most purposes. The removal of the last trace of iron can be readily effected by treatment with phosgene.[2]

The pure oxide has a serious disadvantage for the manufacture of crucibles, in that it is readily reduced either to a lower oxide or carbide—under certain circumstances metallic zirconium may be formed—successive reduction and oxidation give rise to the rapid disintegration of the crucible.

The fused oxide is inert to chemical action. It is not attacked at an appreciable rate by fusion mixture or by molten glass, but dissolves in fused borax. The addition of small quantities (of the order of 1 per cent) of other oxides, thoria, yttria, alumina, etc., enables satisfactory crucibles to be made with a denser body than with zirconia alone.

Coefficient of Expansion.—The value of this is $0{\cdot}84 \times 10^{-6}$, being the lowest of the well-known oxides, with the exception of fused silica.

The Thermal Conductivity is said to be low.

Specific Heat.[3]—

Temperature.	Specific Heat.
0°-100°	·108
25°-600°	·137
25°-1000°	·157
25°-1200°	·167
25°-1400°	·175

REFERENCES—ZIRCONIA

Ruffer, Lauschke, *Sprechsaal*, 1916, 36, 70.
Audley, *Trans. Cer. Soc.*, 1916, xvi. 121.
Ruff, *Zeit. anorg. Chem.*, 1914, xxxvi. 864; 1916, xcvii. 73.
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Weiss, *Zeit. anorg. Chem.*, 1916, xcvii. 73.
Meyer, *Metal Chem. Eng.*, 1914, xii. 191; 1915, xiii. 362.

§ (49) ALUMINA (Al_2O_3).—The source of Al_2O_3 as a refractory in nature is bauxite. The mineral invariably contains considerable quantities of iron and silica and is usually partially hydrated. The cost of purifying the mineral sufficiently to make a satisfactory refractory together with the necessity of a high firing temperature to avoid excessive shrinkage

[1] Washburn and Libman, "The Diagram of the System ZrO_2 SiO_2," *Trans. Amer. Cer. Soc.*, Aug. 1920.
[2] Washburn and Libman, *loc. cit.*
[3] Bradshaw and Emery, *Trans. Cer. Soc.* xix. 84.

in use (as with zirconia and magnesia) prevents the very extensive use of Al_2O_3 for industrial purposes. Bauxite bricks are manufactured and used where the chemical conditions are too basic for fireclay to give satisfactory results. As a basic refractory, however, it is inferior to magnesia.

Laboratory ware made from calcined alumina and bonded with clay is used extensively for furnace cores, pyrometer tubes, crucibles, combustion boats, etc. The ware is generally highly porous (40 per cent porosity or more) and softens under load at a low temperature. Pyrometer tubes will sag under their own weight at 1350° C.

The crushing strength of bauxite and crystalline alumina has been determined by Bodin.[1]

Temperatures . . .	20°	800°	1000°	1300°	1500°
Bauxite fired to 1300°	395	270	715	55	20
Bauxite fired to 1500°	660	360	685	95	15
Crystalline alumina	790	350	615	310	30

Coefficient of expansion 0-1000 is 7×10^{-6}.

Fused alumina is inert to chemical action, being similar to zirconia.

§ (50) Sillimanite (Al_2O_3 SiO_2).—This compound (see *Fig.* 12, p. 487) promises to become of importance. It appears to be highly resistant to the action of slags and offers advantages for use as grog as a substitute for burned fireclay in glass-house refractories. The discovery of large deposits of sillimanite in India has opened out a new field for this material, but, as yet, its development is only in the experimental stage.

§ (51) Silicon Carbide (SiC). — Silicon carbide is commonly known under the name of Carborundum, the name under which this product was first manufactured under the patents of its discoverer, Acheson.

Amorphous carborundum is formed from carbon and silicon at temperatures as low as 1300°, in traces, but is only formed abundantly in the neighbourhood of 1600°. The crystalline variety is produced by the interaction of silica and carbon at about 1900° at atmospheric pressures. Under reduced pressure the temperature of formation is lowered to 1460°. Pring states that SiC is formed under reduced pressure (·01 mm.) at 1250°.[2] An increased pressure inhibits the formation of SiC.

On an industrial scale the manufacture is as follows :

A firebrick furnace $16' \times 5' \times 5'$ or larger is packed with a charge of coke, sand, sawdust, and salt, in approximately the proportions sand 54 per cent, coke 34 per cent, sawdust 10 per cent, and salt 2 per cent. Carbon electrodes are situated at each end of the furnace and these are connected by a cylindrical core—about 20″ in diameter—made up of ¾″ lumps of coke running through the centre of the charge. The function of the sawdust is to increase the porosity and so to facilitate the escape of the CO formed during the reaction. The salt, acting as a flux, increases the reaction velocity, and also, probably, serves to purify the charge by the formation of volatile chlorides. A heavy current is passed through the coke core and a high temperature is obtained. The reaction is :

$$SiO_2 + 2C = Si + 2CO,$$
$$Si + C = SiC.$$

The CO passes up through the charge and burns at the top of the furnace. The heating is continued for about 36 hours and the current consumption during this period is about 6000 amps. (at 125 volts). With this consumption about 3 tons of crystalline SiC are produced and about 2½ tons of amorphous SiC. The total charge is about 14 tons.

The SiC is ground with water, digested with H_2SO_4, washed, dried, and screened.

The theoretical composition of SiC is 30 per cent C, 70 per cent Si. The commercial grades contain :

Si	65-69·5 per cent.
C	28-32 „ „
Al_2O_3 . . .	0·2 -2 „ „
Fe_2O_3 . . .	0·05-1·0 „ „

The amorphous material found surrounding the central crystalline portion of the charge is sold as " fire sand " and used for miscellaneous purposes as a refractory. The average composition of this is :

SiC	80 per cent.
SiO_2	6 „ „
Al_2O_3 . . .	3 „ „
Fe_2O_3 . . .	3 „ „
C (free) . . .	8 „ „

§ (52) Chemical Properties of Carborundum.—SiC is oxidised slowly in air at 1200°, CO and SiO_2 being produced. If heated to 1500° the SiO_2 fuses and glazes the SiC crystals, retarding further oxidation. At 1750° the oxidation is rapid. The temperature of decomposition is 2220°.

Nearly all the metallic oxides react with SiC, forming silicides. The approximate temperatures at which reactions take place are :

CuO . . .	800°
CaO . . .	1000°
MgO . . .	1000°
Fe_2O_3 . . .	1300°
NiO . . .	1300°
MnO_2 . . .	1360°
Cr_2O_3 . . .	1370°

[1] *Trans. Cer. Soc.* xxi. 56.
[2] Pring, *Chem. Soc.*, 1908, xciii.

SiC is decomposed by fused sodium carbonate, sodium silicate, alkali sulphates, borax, cryolite, and caustic potash. Chlorine reacts with SiC at 900° yielding $SiCl_4$. SiC is not attacked by boiling acids (including HF).

§ (53) Physical Properties.—Pure SiC is practically colourless. As usually found it varies ffom pale green to black. The black crystals show iridescence due to a thin film of SiO_2.

Refractive Index—

Red 2·72 (α)-2·8 (β)
Violet 3·4 (α)-3·8 (β)

Specific Gravity.—3·23.

Specific Heat.—·168.

Thermal Conductivity.—For SiC brick at a temperature of 1000°—·0231.

Coefficient of Expansion.—

Temperature.	Coeff. of Exp. $\times 10^{-4}$.
15°-1000°	4·71-4·78

Electrical Resistance.—Determinations made on SiC bricks with and without bonding materials:

Temperature.	Specific Resistance without Bond.	Specific Resistance with Clay Bond.
	Ohms.	Ohms.
25°	50	284,000
100°	46·4	..
200°	39·6	270,000
400°	26·6	250,000
600°	14·6	70,000
800°	7·8	24,000
1000°	3·7	..
1100°	2·1	15,000
1200°	1·3	40
1400°	0·65	..

The properties of SiC make it a valuable refractory for certain purposes. The thermal conductivity is far higher than that of any other refractory material, and therefore, as an ingredient for retorts, muffle tiles, and so on, the use of carborundum effects a considerable saving of fuel. SiC vessels are made by bonding the SiC with a suitable clay. In firing these SiC-clay mixtures it is necessary to attain a temperature exceeding that at which the article is to be used, since these refractories deform under load at high temperatures if lightly fired.

The angularity of the grains makes SiC particularly easy to bond with a clay and, if fired hard, only a small amount of clay, say 5 per cent, is necessary, since the silica formed by the oxidation of the SiC is an adequate bond.

SiC provides an effective wash over the surface of clay refractories exposed to a high temperature, and prevents the clay from running. It can be used on the outsides of crucibles and on furnace walls with beneficial effect. The wash must be renewed from time to time owing to the oxidation of the SiC. The clay used as a bond should be as free from fluxes as possible.

Very dense SiC articles are made by moulding or pressing the desired shapes in carbon bonded with tar. The carbon is then subjected to the action of silicon vapour at high temperatures. The silicon penetrates into the pores and unites with the carbon to form a dense crystalline SiC body without disintegration or warping of the article which is being made.

§ (54) Summary.—In conclusion, a tabulated summary of the principal properties of average refractories, given on the following page, will be found of service.

The following table gives the approximate specific resistance (ohms per sq. cm. per cm. thick, except where stated) of samples of commercial bricks:

Electrical Resistance of Commercial Refractorials [1]

	Cold.	800° C.	900° C.	1000° C.	1100° C.	1200° C.	1300° C.	1400° C.	1500° C.
Silica	125 Meg.	2·38 Meg.	765,000	300,000	126,000	62,000	30,900	16,500	8420
Magnesia	137 Meg.	5·00 Meg.	1·24 Meg.	708,000	560,000	193,000	67,400	22,400	2500
Zirconia (natural) . .	134 Meg.	558,000	224,000	131,300	53,800	7,710	2,100	968	412
Bauxite	133 Meg.	109,000	32,500	17,200	9,200	6,100	5,600	2,200	1100
Fireclay (Grade A) . .	137 Meg.	57,600	20,600	10,800	6,590	4,160	2,460	1,420	890
Bonded carborundum "Carbofrax C" . .	127 Meg.	835,000	477,000	197,000	75,000	29,500	15,200	10,100	8590
Bonded carborundum "Carbofrax B" . .	107,200	12,550	8,220	7,420	6,320	4,160	2,420	1,435	745
Recrystallised carborundum (Refrax), no bonding material . . .	106·9	6·45	5·25	4·11	3·11	2·45	2·05	1·74	1·62

[1] Hartmann, Sullivan, and Allen, *Trans. Amer. Electrochem. Soc.*, 1910, xxxviii. 279.

SUMMARY OF PROPERTIES OF AVERAGE REFRACTORIES

	Normal Refractoriness.	Refractoriness under Load (75 lbs.).	Melting-point.	Boiling-point.	Specific Gravity.	Specific Heat 0°-1000°.	Thermal Conductivity.	Coeff. of Expansion 0-1000 × 10^{-6}.	Chemical Characteristics.	Remarks.
Firebrick, §§ (5-30) . .	Cones 26-35 1580° C., 1770° C.	Cones 12-16 1350° C., 1460° C.	..	..	2·5-2·7	·26	·003	4·5-6·0	Acid	Softens readily under load.
Silica, §§ (31-38) . .	..	..	1670°-1710°	3500°	2·21-2·65	·26	..	0·5 (fused)	Acid	Highly refractory under load.
Silica brick, §§ (37-38) .	33 1730° C.	18-28 1500° C., 1650° C.	..	..	2·3-2·5	·26	·003	10-12	Acid	do. do.
MgO, §§ (47-48) . .	..	..	2800° C.	3600°	..	..	..	..	Basic	Volatile at high temperatures. Not reduced by carbon.
Magnesite brick, §§ (47-48)	Over Cone 40 2000° C.	Cone 16 1460° C.	..	..	3·4-3·6	..	·01	13·5	Basic	Softens readily under load.
ZrO_2, §§ (49-50) . .	Over Cone 40 2000° C.	..	2700° C.	4300°	4·8-5	·15	..	0·8	Neutral	Easily reduced and oxidised. Fused oxide resistant to fluxes.
Al_2O_3, § (51) . . .	Over Cone 40 2000° C.	..	2050° C.	3800°	3·9	..	·003	7·0	Neutral (slightly acid)	Volatile, reduced at high temperatures. Fused oxide resistant to fluxes.
SiC, §§ (53-55) . . .	Over Cone 40 2000° C.	..	decomp.	2220°	3·23	·168	·0231	4·75	Acid	Oxidised at 1200 slowly, rapidly attacked by alkalis, metallic oxides, etc.
Graphite-clay . . .	..	..	..	..	2·25	·4	·014	7·9	..	Insensible to sudden temp. changes.
Porcelain (Berlin) . .	Cone 30 1670° C	Cones 8-10 1280° C.	..	..	2·2-2·5	·25	·0025	4·3	..	Very brittle to changes of temperature.

The analyses of the materials are as follows:

	SiO_2. Per cent.	Fe_2O_3. Per cent.	Al_2O_3. Per cent.	CaO. Per cent.	MgO. Per cent.	TiO_2. Per cent.	ZrO_2. Per cent.
Silica	94·8	0·2	1·8	2·4	0·3	..	..
Magnesia	6·0	0·3	6·3	3·1	84·1	..	..
Zirconia (natural) . . .	21·5	0·7	4·7	0·0	0·0	0·5	72·6
Bauxite	40·4	0·9	55·5	0·2	0·0	2·7	..
Fireclay	50·4	0·8	45·5	0·5	0·8	1·9	..

The bibliography of refractories is scattered throughout almost all branches of technical literature of a metallurgical or general scientific nature. Papers dealing with refractories are to be found in the publication of The Faraday Society, Iron and Steel Institute, Ceramic Society, American Ceramic Society, Society of Glass Technology, American Inst. of Mining Engineering, and in *Revue de Mét. Comptes Rendus, Sprechsaal*, Technologic Papers of the Bureau of Standards, U.S.A., and many others.[1]

E. A. C.-P.

REFRACTORIES USED IN GLASS-MAKING

§ (1) Introductory.—The refractory materials used in the manufacture of glass can be divided into two broad classes, viz. those which are in actual contact with the molten glass and those which, whilst exposed to the action of dust or volatile products of glass-making reactions, are not in direct contact with the molten glass. For both classes, resistance to prolonged exposure to high temperatures is essential; but, in addition, the refractories (such, for example, as pots and tank-blocks) which are in direct contact with molten glass must resist the corrosive action of the glass batch and of the molten glass. These refractories, such as pots, which are required to hold a considerable weight of molten glass and are exposed to high temperature on both inner and outer surfaces must possess a high mechanical strength at founding temperatures. The founding temperatures necessary for efficient glass-melting are rarely, if ever, so high as those necessary for such metallurgical operations as steel-melting. Glass-melting furnaces seldom exceed a temperature of 1500°-1550° C., so that from the purely temperature point of view the conditions are not very severe, but in all cases of exposure of refractories to high temperatures the time factor is one of major importance. The run of a steel-melting furnace does not often exceed eight or ten weeks, but in a glass-melting tank the full heat is maintained for as long, in some cases, as two years, whilst a life of from eight weeks to as much as thirty or forty weeks is expected from glass-melting pots, except in the special case of those used for optical glass-melting. From the time point of view, therefore, the glass furnace conditions are much more stringent than are those of the steel-melting furnace.

§ (2) Silica Bricks.—In those parts of both pot and tank furnaces which are not exposed to direct contact with molten glass—such, for example, as the crown and upper portions of the walls, the pillars of pot furnaces, the ports of tank furnaces—silica bricks or blocks are almost invariably employed. The temperatures and conditions met with in both types of furnace are such as to be favourable to a long life for silica bricks of good quality in such situations. The most important difference in the behaviour of fireclay and silica refractories is that on the first continued heating the clay will shrink [1] and the pores close up, while with the latter the inversion into a lighter form of silica will cause a permanent increase in volume. This tendency of silica bricks to expand on continued exposure to high temperature is an important factor in their use, as in crowns and pillars in particular the absence of shrinkage is desirable in order to maintain the mechanical stability of the structure. Semi-silica bricks in which the proportions of fireclay and silica are so adjusted that the shrinkage of the fireclay is neutralised by the swelling of the silica, whilst rather less refractory than silica bricks, are also occasionally used for positions in which constancy of volume is important.

A further important factor in connection with the use of silica bricks in the crowns of furnaces is that "droppers" formed by the action on the bricks of alkaline dusts and vapours are readily soluble in the glass and therefore do not form "stones."

The manufacture and properties of silica bricks are discussed in the article on Refractories, §§ (29), (36).

The texture of a silica brick is important.

[1] See also *Refractory Materials*, A. B. Searle; *A Treatise on the Ceramic Industries*, A. Bourry; *Refractories and Furnaces*, Havard; *The Clayworkers' Handbook*, Searle; *Fabrication et emploi des matériaux et produits réfractaires*, Granger; *Die feuerfesten Tone*, Bischof; *Die Herstellung der feuerfesten Baustoffe*, Wernicke.

[2] See "Refractories," §§ (9), (33).

Assuming that its chemical composition and refractoriness are otherwise satisfactory, the behaviour of the brick will largely depend on its texture. On examination, a silica brick is seen to consist of fragments of crystalline silica set in a matrix which is often glassy in character and is mainly composed of calcium-silicates, calcium-iron-silicates, and calcium-alumino-silicates. The size and shape of the fragments of silica have a definite influence on the behaviour of the brick. The brick should be composed of angular fragments of varying size from $\frac{1}{4}$ inch downwards, together with a proportion of fine powder, so that, as in concrete, there shall be as few voids as possible. The coarser-grained open-textured bricks will resist abrupt temperature changes better, but will be less resistant to the penetrating action of dust or vapours from the glass batch and to the abrasive action of hot gases. The texture to be selected will depend on the conditions under which the brick is to be used, but in the majority of situations in the glass furnace, bricks of uniform texture containing no fragments larger than, say, $\frac{1}{4}$ inch diameter will give the best results. Whether the texture selected be coarse or fine, however, it should be uniform throughout the brick. In average unused silica bricks a large proportion of the silica is still in the form of quartz, there being only partial conversion into tridymite and cristobalite. A silica brick which had been in use for several years in the crown of a glass tank-furnace with a normal founding temperature of 1350° C. was recently examined by the author. It showed three distinct divisions: the end which had been exposed to the furnace consisted almost entirely of tridymite with some cristobalite (see *Fig.* 1); the middle portion showed indications of some inversion to tridymite and was slightly fissured, whilst the outer portion of the brick was unchanged. The total increase in volume of the silica brick during its use in the furnace may be divided into three phases, each caused by the action of different factors. There is, first, the temporary increase which is reversible, and is compounded of the usual thermal expansion and the volume change from the α-β quartz inversion. This volume change cannot be avoided, and, as it is considerable, great care is essential in heating up a silica brick structure. The rise in temperature must be gradual and regular, and the furnace tie-rods must be slackened at frequent intervals or the stresses set up would cause them to snap, with disastrous effects to the structure. In cooling the furnace the converse precaution is equally necessary. Secondly, there is the permanent expansion due to the inversion of the original quartz to tridymite or cristobalite; and, thirdly, there is the increase in volume due to the fact that the newly formed crystals of tridymite or cristobalite are not so orientated as to occupy the minimum volume. It is undesirable that the silica bricks used in glass furnace construction should contain more than 20 to 30 per cent of unconverted quartz, particularly when used in building walls and pillars where expansion accommodation cannot readily be provided. Even in crowns, etc., where expansion can be allowed for, a low content of unconverted quartz is advantageous, as changes in shape or contour are avoided.

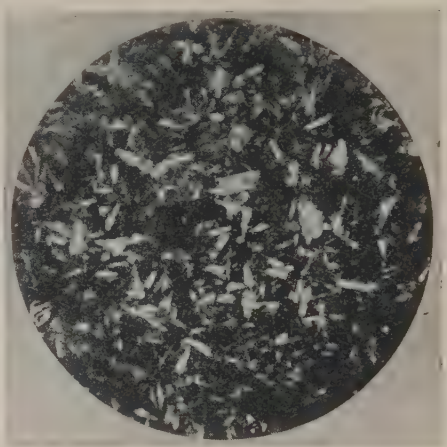

Fig. 1. ×25.

§ (3) Mechanical Properties and Tests. — The mechanical strength of the bricks is important for situations in furnaces, etc., where loads have to be carried. It has been suggested (American Ceramic Society report on tentative specifications for glass works refractories) that the effective modulus of rupture of silica bricks could be easily measured and that a standard 9-inch brick, supported on knife edges with a 6-inch span, should have an effective modulus of rupture of not less than 500 lbs. per square inch. Bricks which conform to the following specification should give satisfactory results in practice.

(*a*) *Chemical Composition.*—The bricks shall contain not less than 94 per cent of silica and not more than 2 per cent of lime.

(*b*) *Refractoriness.*—Test-pieces shall not be more fusible than Cone 32 (1710° C.) when tested under standard conditions. (See note (i.).)

(*c*) *Apparent and True Specific Gravity.*—The apparent specific gravity shall not be less than 1·60 and the true specific gravity not higher than 2·40. (See note (ii.).)

(*d*) *Mechanical Strength.*—The cold crushing

strength of the brick tested on end shall not be less than 2000 lbs. per sq. in.

Under a load of 50 lbs. per sq. in. the brick shall not crush or squat at a temperature lower than that equivalent to Cone 20 (1530° C.).

It is desirable that the surfaces of the bricks should be true so that they may be used with the minimum quantity of cement. There should not be a greater variation from any specified dimension than ± 2 per cent.

(i.) *Tests.*—The Standard Methods of Testing of the Ceramic Society are recommended. Silica, in common with most refractories, has not a definite softening temperature, but there is a range of temperature within which it begins to lose its shape and commences to flow. Two distinctive properties of silica refractories may be referred to here. Melts derived from silica have a very high viscosity and thus form a thick protective fluid layer; the melting-point curve is a flat one, and therefore at high temperatures a large proportion of silica remains in the solid state even in the presence of marked quantities of impurities. A further factor of importance is the high reflecting power which molten silica possesses; heat loss through the brickwork is therefore diminished, whilst the intensity of radiation in the furnace is maintained.

(ii.) *Specific Gravity.*—The true specific gravity (or powder density) is not an absolutely definite indication of the extent of conversion of the quartz, owing to the effect of variations in the proportion of lime or other bonding ingredient present in the brick. With all normal types of brick, however, a powder density of 2·32 would indicate a fairly complete conversion of the quartz, whilst 2·40 would indicate the presence of about 30 per cent of unconverted quartz.

(iii.) *Silica Cement.*—The minimum quantity of cement to secure proper jointing should be used, and in building crowns and arches it is good practice to lay the bricks dry and apply the cement as a grouting. The cement should be only slightly less refractory than the bricks with which it is to be used, and it should invariably be finely ground.

It is essential that silica bricks should be adequately protected during storage. Exposure to a moist atmosphere, and more particularly exposure to rain, causes a considerable diminution in mechanical strength.

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Rees, "Silica Refractories for Glassworks Use," *Jour. Soc. Glass Tech.*, 1918, 253.

"Standardisation of Tests for Refractory Materials," *Trans. Cer. Soc.* xvii. 300.

Rees, "Critical Review of Provisional Specifications," *Jour. Soc. Glass Tech.* vi. 181.

Thomas, Hallimond, and Radley, *Special Reports on Mineral Resources of Great Britain*, vol. xvi.

Johns, "Glass Industry Refractories," *Jour. Soc. Glass Tech.* i. 127.

§ (4) POT FURNACES.—The lower portions of the walls of pot furnaces may be constructed of fireclay bricks or blocks. Modern gas-fired furnaces are of two types, recuperative and regenerative. The siege or floor of both types should be constructed of fireclay blocks which will withstand the corrosion of glass and must be sufficiently well burned to inhibit further contraction during use. For moderately high temperatures such as those employed in the melting of lead glasses for table ware, etc., the limits of chemical composition and physical properties of siege blocks are wide, but in high-temperature furnaces the conditions are more stringent. In the latter case the refractoriness should not be lower than Cone 30, the volume porosity not greater than 30 per cent, and the after-contraction (under standard test) should not exceed 1·5 per cent linear. Very high temperatures are frequently developed in the "eye" of recuperative furnaces, and for such situations high refractoriness and adequate burning of the blocks is essential.

§ (5) RECUPERATORS.—The bricks employed in the building of recuperators must be of low porosity, must not develop cracks on long heating at temperatures up to 1000°-1100° C., or exhibit any marked permanent volume changes. Cracks or shrinkage in the bricks, tubes, or tiles may lead to the development of leakages which would seriously impair the efficiency of the recuperator. The recuperator may be constructed of (*a*) adequately burned fireclay material. The after-contraction under standard test should not exceed 1 per cent; and, especially where tiles are employed, the mechanical strength at the recuperator temperature must be sufficient to prevent sagging. (*b*) Adequately burned semi-silica material (80 to 85 per cent silica). In the use of this type of refractory, as with silica refractories, care in heating is essential. Cobb and Houldsworth have shown that the presence of the clay only masks the volume changes due to the α-β quartz inversion to a very slight extent, unless the quartz has been finely ground and the quartz-fireclay mixture highly burned. (*c*) Highly converted silica material with a fine matrix and uniform texture. Its higher thermal conductivity renders this material very advantageous for the purpose. The after-expansion of 95 per cent silica material containing not more than 20 per cent of unconverted quartz will be small.

§ (6) REGENERATORS.—In modern practice, silica bricks are used for the filling of regenerators in preference to fireclay bricks, because of their greater mechanical strength at high temperatures and their higher resistance to the fluxing action of dust which may be brought in with the gas or carried over from the furnace. A coarse-textured brick with a porosity of 25 to 30 per cent should be used. The best

thickness of brick for efficient heat interchange is from 2 to 2½ inches.[1] A periodic cleaning of regenerators is desirable, in order to remove loose dust; such apparently drastic methods as firing a small charge of coarse black powder into the lower portion of the regenerator or (when firebrick fillings are employed) washing out with a high-pressure water hose give good results.

§ (7) Pots.—Glass-melting pots are made from a mixture of a plastic refractory clay with "grog," which may be either carefully cleansed potsherds or fireclay pre-burnt at a high temperature. The quantity of "grog" which may be used depends on the binding power, plasticity, and grain of the clay; with "fat" clays as much as 60 per cent (by volume) of the mixture may be used, but with "lean" clays, such as those of Stourbridge, the proportion seldom exceeds 20 per cent. Modern practice is tending in the direction of using more complex mixtures, particularly for pots for the melting of the newer types of glass such as laboratory and resistant illuminating glassware, which necessitate a high founding temperature. Three or more constituents may be used in these mixtures, viz. a plastic or "bind" clay, a refractory base clay, and grog or fireclay which has been previously burnt at a high temperature. In order to obtain uniform resistance to corrosion it is desirable for the grog to be prepared from a mixture of the raw clays employed or to have a similar degree of resistance to solution or corrosion as the mixture of raw clays. Much discussion has taken place during the last few years as to the relative merits of aluminous and siliceous pot-clay mixtures. Whilst, in general, aluminous clays are more resistant to the corrosion of complex types of glass, there are several factors which need consideration before such mixtures are adopted: first, their great (and often continuing) contraction at high temperatures; second, their low mechanical strength at high temperatures, which may, especially with heavy glasses, lead to bulging of the pot wall and even to actual collapse of the pot; third, their tendency to cause "wreathy" or "stringy" metals because of the difference in viscosity between the layer of glass in contact with (and interacting with) the pot wall and the rest of the glass.

Siliceous clays have, in general, a smaller contraction than aluminous clays, and pots made from them have a greater mechanical strength at founding temperatures. Because of this, pots, such as plate-glass pots, which are handled while at a high temperature are frequently made from admixtures of high-silica sand with fireclay, in order to give them the necessary mechanical strength. For normal glass-making, good results are obtained from pot-clay mixtures giving about 70 per cent of silica in the burnt pot. When, to obtain necessary resistance to corrosion, aluminous mixtures are used, it is essential to use as large a proportion as possible of highly burnt grog, in order to reduce shrinkage. The grog employed must always be angular in character, so as to obtain good packing and offer the maximum surface to the binding action of the raw clay. The pot-clay mixture, when tempered with the correct proportion of water so that the maximum tensile strength of the plastic clay is obtained,[2] should when subsequently fired have a regular shrinkage curve, should burn dense at 1350°-1400° C., and should not exhibit indications of over-firing ("bloating") at 1500° C. Some of the siliceous clays show breaks in the shrinkage curve at 600°-700° C. due to the α-β inversion of the quartz present. The drying shrinkage of the mixture should not exceed 15 per cent by volume, and the shrinkage over the temperature range 1150°-1450° C. should not exceed 4·5 per cent by volume. A table of chemical analyses for typical pot-clays is given on the opposite page.

§ (8) Manufacture of Pots. (i.) *Hand-made Pots.*—When the pots are to be made by hand, either with or without moulds, the tempered mixture of clay and grog is stored in a cool dark place for a period varying from one to six months, so that it may *mature* or *sour*. During this storage, uniformity of distribution of the water is secured, and there is frequently a definite increase in plasticity and toughness due to hydrolysis and probably to flocculation. In some cases the clay is pugged or "trodden" at intervals during the *souring* period; if pugging is adopted it is important that the angle of blade in the pug is such that air-bubbles are not drawn into the clay. In building by hand without a mould it is customary to suspend the operation at intervals, in order to obtain uniform drying as the thickness of the clay decreases. Small pots are successfully made by ramming the plastic clay into a wooden mould, but although much time may be saved by the employment of a mould or shape, this method is not to be recommended for large pots from which the maximum *life* is desired. Elimination of air-bubbles is difficult and uncertain, and freedom from lamination is not easily secured. With covered pots, when moulds are employed, the hood is made separately, and subsequently joined to the body of the pot. This plan is also adopted occasionally when hand-building is employed. C. W. Thomas has suggested a method of joining the two portions of the pot with an asbestos cement.[3]

[1] See Clements, "The Open-Hearth Furnace," *Jour. Iron and Steel Institute*, 1922.

[2] See "Refractories," § (6).

[3] *Trans. Soc. Glass Tech.* iv. 107.

CHEMICAL ANALYSES FOR TYPICAL POT CLAYS

	Stourbridge.		Yorkshire.		Germany.			Belgium.			France.	America.
	Strong.	Mild.	Huddersfield.	Halifax.	Gross Almerode.	Klingenberg.	Markt-Redwitz Chamotte.	Mozet, St. Hubert.	Delforges. Fat.	Delforges. Lean.	Provins.	Commercial Pot Clays.
SiO_2	65·90	55·71	66·63	56·76	71·07	50·76	56·56	63·44	53·51	62·49	61 to 70	74·62
Al_2O_3	21·64	27·94	20·46	26·58	17·64	29·26	40·43	24·55	28·70	22·13	20 ,, 25	16·12
TiO_2	0·96	1·06	1·17	1·09	0·91	1·61	..	0·91	0·76	0·81	0·5 ,, 1	1·06
Fe_2O_3	1·64	1·76	2·41	2·94	1·81	1·51	1·86	1·62	1·49	0·96	0·5 ,, 3	1·52
CaO	0·46	0·51	0·16	0·18	0·24	1·08	0·41	0·71	0·51	0·61	0·3 ,, 1·5	0·32
MgO	0·35	0·40	0·31	0·40	0·38	0·73	0·19	0·21	0·19	0·4	0·5 ,, 1·3	0·26
K_2O	0·69	0·71	0·51	0·91	0·41	0·85	} 0·76					
Na_2O	0·18	0·36	0·31	0·36	0·34	0·19		1·21	1·16	1·04	0·5 ,, 1·0	0·96
Loss on ignition	8·12	11·46	7·94	10·70	7·14	14·24	..	7·26	13·62	11·70	7 ,, 12	5·40
	99·94	99·91	99·90	99·92	99·94	100·23	100·21	99·91	99·94	99·88	..	100·26
Normal Refractoriness	Cone 29	Cone 31	Cone 29	Cone 30	Cone 29	Cone 30	Cone 34	Cone 29	Cone 30	Cone 29	Cones 28-31	Cone 28
												Cone 29

* Contains approximately 40 per cent of grog.

(ii.) *Slip-casting of Pots.*—This method of pot-making is employed to a considerable extent in Germany and to a lesser extent in England and America. By use of suitable deflocculents a dense slip is obtained. With clays of low plasticity much larger proportions of grog or other non-plastic ingredient may be used when slip-casting is adopted. In deflocculated slips of high density (40-45 oz. per pint) there is little or no settling of the grog. It is desirable to ascertain experimentally the best deflocculator to use for any particular clay or mixture; with the majority a mixture of sodium carbonate and sodium silicate is satisfactory, but with some clays a better slip is obtained by substituting sodium hydrate for sodium carbonate.[1] Weber[2] has referred to the gelatinising action of certain soluble salts (*e.g.* sulphates of calcium and the alkalies) occasionally present in clay and to the necessity for their neutralisation by precipitation (barium carbonate or hydrate may be used) before proceeding with the deflocculation. A satisfactory slip will contain very little more water than is present in a plastic clay of proper consistency for pressing or throwing, *i.e.* from 15 to 20 per cent; it should remain liquid for some time when at rest, so that when the mould is filled the difference in volume caused by water absorption by the plaster mould is equalised by the still fluid slip. Irregular contraction and resultant cracking of the cast pot are thus obviated. The use of hot water in the preparation of slips is frequently advantageous. The following are examples of the clay and deflocculent content of satisfactory slips for pot-casting:

With Stourbridge clay:

Per litre of water:
- 3400 grm. Clay.
- 850 ,, Grog.
- 4 ,, Barium hydrate.
- 5 ,, Sodium carbonate (anhydrous).
- 9 c.c. Sodium silicate, density 1·3.

With Meissner clay:

Per litre of water:
- 2300 grm. Clay.
- 2400 ,, Grog.
- 5 ,, Sodium carbonate (anhydrous).
- 2 c.c. Sodium silicate, density 1·3.

With American pot-clay mixture:

Per litre of water:
- 4500 grm. Pot clay (containing 25 % grog).
- 5 ,, Sodium silicate, density 1·6.
- 0·5 ,, Sodium hydrate.

The vacuum casting process of B. J. Allen[3] presents certain advantages for casting complex shapes, but for normal-shaped pots, etc., a simple mould and core is quite satisfactory.

[1] See "Refractories," §§ (7), (15).
[2] *Trans. Cer. Soc.* viii. 1.
[3] *Trans. Soc. Glass Tech.* iii. 78.

§ (9) The Lining of Pots.—Increased resistance to corrosion may be obtained by lining pots with a material which on firing gives a dense body adhering well to the pot wall. Mixtures of a refractory clay (*e.g.* china clay) with from 5 to 15 per cent of felspar give a satisfactory lining which on firing at 1300°-1400° C. is porcellanic in character. The lining is applied, during the building of the pot, in a thickness of one-quarter to one-half inch up to the metal line and is continued upwards for 6 to 9 inches in gradually diminishing thickness. Difficulties may be experienced with lined pots if the contraction of the lining is excessive; the sudden cooling produced by the insertion of cold batch into the hot pot may also cause cracks in the vitrified lining.

§ (10) The Drying of Pots is an operation requiring considerable care and control. Irregular drying may set up strains which will cause cracking of the pot: occasionally cracks so formed may be so minute that they only become evident during the subsequent heating of the pot.[1] Drying may be safely expedited by employing chambers in which the humidity is controlled. "Humidity dryers"[2] are now installed in some of the modern pot-making plants, particularly in America. After drying it is customary to store the pots for upwards of one month at a temperature of about 65° F. in order to "season" or completely air-dry them.

§ (11) The Pot Arch.—In this the preliminary heating of the pot, prior to its transfer to the furnace, is conducted. It is generally coal or coke fired, but gas-firing is now very frequently adopted. Pyrometric control of the rate of heating is desirable. The rate of heating over the temperature range, 450°-650° C., during which the clay is dehydrated and the α-β change takes place in the quartz present in the clay, must be slow. A satisfactory heating schedule for normal-sized pots is: 1 day, 75° C.; 2 days, 100° C.; 3 days, 350° C.; 4 days, 550° C.; 5 days, 700° C.; 6 days, 900° C.; 7 days, 1100° C.

§ (12) Vitrification of the Pot.—At the maximum pot-arch temperature the pot is still in a "biscuit" condition. In this condition it absorbs and is readily attacked by molten glass, the rapidity of the attack increasing rapidly with rise of temperature. After transfer to the furnace it is therefore desirable to heat the pot to the temperature (1300°-1400° C.) at which vitrification takes place in the particular clay mixture concerned, before glazing or filling on cullet or batch. The vitrified clay may be considered as a solid solution of aluminium silicate with free alumina or silica, and in contact with the alkaline glass batch the free silica or alumina dissolves and there is a separation of aluminium silicate in the form of sillimanite. If the pot is completely vitrified before glazing, a uniform layer of sillimanite is formed on contact with the glass, but if glass is brought into contact with the biscuit clay the formation of sillimanite will be irregular, and internal corrosion and vitrification may proceed simultaneously. Shepherd and Rankin have investigated the formation of sillimanite from melts containing silica and alumina (see diagram for binary system $Al_2O_3 - SiO_2$).[3] The formation of a uniform internal layer of sillimanite considerably retards the corrosion of the pot wall. With aluminous clays corundum may crystallise from the melt formed on contact with molten glass. E. M. Anderson has suggested a diagram (*Fig.* 2) to illustrate the conditions existing at any given time in such cases.[4] The horizontal component represents

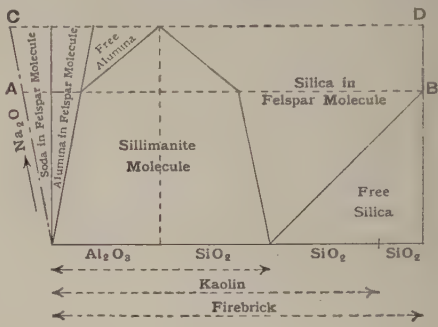

Fig. 2.

the composition of the clay (one molecule of kaolin with a little excess silica). Soda is added along the vertical ordinate, the horizontal distance between the vertical and oblique lines representing the molecular proportion of soda present at any given time. At the section AB a felspar molecule Na_2O, Al_2O_3, $6SiO_2$ and a proportion of sillimanite are present; below AB some free silica occurs. Above AB free alumina occurs, and as the proportion of soda increases the sillimanite is absorbed, its silica and some of its alumina going to form felspar; when CD is reached the whole of the sillimanite is absorbed and the free alumina crystallises as corundum. The pot is gradually corroded as the absorption of soda increases.

§ (13) "Life" of the Glass-house Pot.—This (assuming the pot to be physically sound when brought into use) is dependent upon the composition of the glass batch which determines the chemical interaction between glass and pot, the temperature of melting, and the viscosity of the resultant glass, and may vary from only a

[1] See "Refractories," § (17).
[2] See *ibid.* § (14).
[3] See "Refractories," § (21).
[4] *Trans. Soc. Glass Tech.* ii. 204.

few days in the case of such corrosive glasses as cryolite-fluorspar opal to upwards of a year with lead glasses such as are manufactured into high-grade tableware. Other factors, such as abrupt changes of furnace temperature, local overheating from defective gas-air balance in the furnace or defective furnace design, chilling from contact with large quantities of cold (or wet) batch, have an important influence on pot life, but are largely under the control of the glass manufacturer. Dr. W. Rosenhain has pointed out [1] that for every glass there may be a certain range of temperature above which that glass attacks the pot with undue rapidity. It should be possible to determine experimentally for a given glass and pot clay a curve connecting the rate of pot attack with temperature; such a curve would indicate the maximum temperature range which could be employed. Experiments conducted at the National Physical Laboratory indicate the important effect of the circulation arising in the pot as the result of changes of density produced by the interaction of the glass and the wall of the pot. The density of a molten glass of normal type is lowered by the solution of clay in it, and an upward current along the pot wall will be caused. This upward flow is compensated by a downward flow a little further from the pot wall; contact of this current of fresh glass with the pot increases the rate of corrosion, and may very largely account for the relatively greater corrosion on the bottom of the pot and the lower portion of the pot walls. It should be noted, too, that the pot bottom may be less vitrified than the wall of the pot, and, as the more resistant layer of sillimanite will not have developed, that portion of the pot will be more susceptible to glass attack. Similarly, the formation of surface currents from the centre to the walls of the pot accentuates corrosion at the metal level and results in the grooving of the pot.

A frequent cause of pot failure is the "drilling" of the bottom or the formation of "shot holes." This may be due to the presence of impurity, such as pyrites, in the pot clay, but is also explainable by the "circulation" theory. A shallow depression may rapidly deepen itself in the absence of a sufficiently vigorous circulation in the pot as to withdraw glass continually from the depression. The entire attack phenomena of the pot would be reproduced in the depression, and the corrosion on the bottom of the depression would be accentuated as the more soluble layers of clay are exposed until, ultimately, actual "holing" occurs. Local corrosion may consequently depend on the precise nature and extent of the circulating currents set up in the pot during the founding, or even during the working, of the metal. The establishing of this *circulation law* (by Rosenhain and Coad-Pryor) governing the corrosion of the pot during glass-melting is an important advance in the study of the mechanism of the interaction of pot and glass.

[1] *Trans. Soc. Glass Tech.* iii. 93.

§ (14) Pots for Optical Glass Melting.—Since pots for this purpose are, in general, used for one melting only, they can be made considerably thinner in the wall. As, in some cases, it is necessary to found at much higher temperatures than is customary in continuous glass-melting in pots, the pot must be highly refractory and must have sufficient mechanical strength at founding temperatures to carry the weight of the charge of molten glass. The pot must offer a high resistance to the attack of the melting batch and molten glass—many of the special types of optical glass are very active in this respect—in order to avoid contamination of the glass and the disturbance of homogeneity through the stirring into the glass of the layer from the pot wall. Careful selection of the pot-making materials is therefore essential. The colouring effect of iron oxide on some optical glasses, such for example as barium crowns and flints, is very marked, and the iron oxide content of the pot must necessarily be low since that impurity is very readily dissolved by the glass. The desiderata may therefore be stated as follows:

(*a*) Refractoriness sufficient to withstand founding temperatures of 1500°-1550° C.

(*b*) Mechanical strength sufficient to withstand the hydrostatic pressure of the molten charge at founding temperature.

(*c*) High resistance to the solvent action of active glasses.

(*d*) Low content of impurities which will dissolve in and colour the glass.

Conditions (*a*) and (*b*) are easily met, but (*c*) and (*d*) present difficulties which are not readily overcome. The use of selected clays which have been purified by blunging and settling after deflocculation or by "osmosing" is one method of meeting the difficulty, and the use of special linings of a mixture of purified china clay and pure felspar is another. European practice has lain mainly in these two directions, the pots being subsequently built by hand or in some cases made by slip-casting. It is essential that the grog used should be highly calcined and, when crushed, of an angular character, and the pot-clay mixture should be adequately matured. As in ordinary glass-melting in pots, the physical condition of the pot is an important factor in its resistance to corrosion. If the surface of the pot has been made dense by vitrification it is more resistant to the solvent action of glass. The activities of the American Geophysical Laboratory [2] in optical glass production have resulted in a method of removing the iron oxide from a

[2] *Journ. Amer. Ceram. Soc.*, 1919, 356.

glass pot by passing chlorine gas into it whilst at a temperature of 1000°-1200° C. The chlorine is introduced into the pot so that it first impinges upon the bottom in order to remove iron where the corrosion during melting is greatest. The ferric chloride formed volatilises and oxidises on issuing from the pot, a deposit of haematite crystals being formed on the outer surface. The experiments showed that the iron oxide content of the pot could be readily reduced by one-half; unfortunately the porosity of the pot was increased by this removal of iron oxide and pot corrosion correspondingly increased, so that the iron content of glass melted in treated pots was not appreciably less than that melted in untreated pots. There is, however, good reason for the contention of these experimenters that with special heat treatment the disintegrating effect of the chlorine upon the pots could be overcome. American practice[1] in optical glass-pot making has, since 1917, developed in the direction of the production of pots of porcelain type. The grog used was made by calcining to cone 14 (1410° C.) a mixture 80 per cent kaolin, 10 per cent flint, and 10 per cent felspar, but this was subsequently satisfactorily replaced by waste bisque from white ware potteries of the approximate composition, 35 per cent kaolin, 15 per cent ball clay, 14 per cent felspar, and 36 per cent flint. The refractoriness of this bisque is equivalent to that of cone 30, but because of its high silica content it carries load well at high temperatures. The pots are made both by hand and by casting. A typical mixture for making by hand is:

	Per cent.
White ware bisque through 10-mesh	35
Selected sherds from old pots through 10-mesh	10
Felspar	3
Flint	4
Tennessee ball clay No. 5	15
Illinois bond clay	5
Kaolin	28
	100

The composition of the mixture for casting is:

	Per cent.
White ware bisque through 10-mesh	48
Plastic bond clay	23
Kaolin	24
Felspar	5
	100

The slip used contains 20 per cent of water, 0·2 per cent of a mixture of equal parts of sodium silicate and sodium carbonate being used for deflocculation. Very good results have been obtained from these porcelain pots; it is essential that they should be adequately burned at 1400° C., in order to vitrify them, before any batch is filled on. Progress in the production of efficient pots for optical glass melting undoubtedly lies in the development of semi-porcelain pots made by casting, as raw materials of lower iron content can be used, and denser, more homogeneous bodies can be produced.

The considerations as to chemical and physical properties of pots apply in their entirety to the production of the clay rods used for stirring the molten glass in order to obtain homogeneity throughout the pot. It is necessary that these rods should have a fine-grained close texture (their volume porosity when burned should not exceed 20 per cent), should be highly resistant to the solvent action of the molten glass with which they will come in contact, and should have sufficient mechanical strength at the highest temperature of use to prevent distortion or abrasion by friction. Before introduction into the molten glass the stirring-rods should be burned to a high temperature so that their maximum resistant properties may be developed.

§ (15) Tank Blocks.—The blocks which are used for lining the sides and bottom of tank furnaces must be sufficiently refractory to resist deformation at furnace temperatures, must be highly resistant to the solvent action of the melting batch and molten glass, and must resist the abrasive action of the moving glass. Fireclay blocks are almost invariably used in modern furnace practice, although blocks of "firestone" (a highly siliceous fine-grained sandstone) are still occasionally employed where the temperature conditions are not severe.

Fireclay tank blocks are made from a mixture of plastic clays with varying proportions of non-plastic clay and grog. As in pot clays, it is desirable that the grog should be well burned, should break into angular fragments, and should have approximately the same resistance to the solvent action of molten glass as the clay matrix in order to reduce the possibility of uneven wear. Except in certain portions of the bridge-wall of tank furnaces, only one face of the block is exposed to the high temperature of the furnace, and the high-temperature load-carrying capacity of the refractory is consequently of not such vital importance as it is in the case of pots. It is therefore possible to employ in tank-block making the more aluminous fireclays and so increase resistance to corrosion. The proportion of grog employed varies within wide limits; with some British clays it is as low as 20 per cent, whilst with some of the fat continental clays as much as 50 to 60 per cent is used.

[1] *Journ. Amer. Ceram. Soc.*, 1918, 15.

The plastic clay mixture is prepared and matured as with pot clays. It is then worked by hand into wooden moulds of the requisite dimensions, with occasional tamping or beating so as to obtain a compact dense mass. Occasionally in European practice, and almost invariably in American practice, pneumatic rams are employed to press the clay into the moulds; in this case it is important to take precautions to avoid lamination. In both hand-moulding and mechanical pressing, air inclusions must be rigorously avoided. Blocks are also made by slip-casting into plaster-lined moulds; the larger field of selection of clays and grog, and the homogeneity and density it is possible to obtain by this process, are very distinct points in its favour.

Special care is necessary in uniformly drying large blocks to prevent the formation of fine crizzles. The adoption of humidity dryers would be advantageous, as the safe and efficient drying would be facilitated and the time of drying very considerably reduced.

§ (16) Firestones.—When "firestone" blocks are used for tank walls it is essential that they should be laid with their bedding planes horizontal so as to avoid flaking or spalling of the exposed face; for tank bottoms the bedding-planes should, for the same reason, be vertical. Sufficient space must be left between the blocks to allow for the expansion resulting from the inversion of the quartz which will take place at furnace temperatures. The stone should contain only a small proportion of micaceous or felspathic impurities or it will not be sufficiently refractory.

A typical analysis of a suitable firestone from Penshaw, Durham, is as follows:

	Per cent.
Silica	88·56
Alumina	6·48
Iron oxide	0·74
Titanium oxide	0·61
Lime	0·31
Magnesia	0·35
Potassium oxide	0·78
Sodium oxide	0·38
Loss on ignition	1·71
	99·92
Normal refractoriness	Cone 29

The uniform texture of firestones tends towards an even corrosion of the block face, but their chemical resistance is generally too inadequate to permit their use in the melting end of high-temperature tank furnaces.

§ (17) Burning of Tank Blocks.—The early stages of the burning must be slowly conducted and the rise of temperature must be gradual so that the centre of the block is as efficiently burned as the skin. Too rapid heating may cause the contraction and reduction in porosity of the skin of the block and so prevent ready access of air to the interior; the carbonaceous and ferruginous impurities present in the clay will be incompletely oxidised, and a dark-coloured core will be left having quite different physical properties from the properly burned outer portions. In extreme cases of "black-hearting" partial slagging of the core may occur through interaction between ferrous iron and free silica present in the clay. A fracture of a block which has been efficiently burned will show a uniform colour right through. A temperature not lower than 1300° C. should be attained during the final stage of the burning, and it is advantageous to maintain this maximum temperature for a day or more. For flux-line blocks higher burning temperatures (up to 1400° C.) are desirable in order to induce vitrification and low porosity.

§ (18) Tests on Tank Blocks.—In selecting or testing tank blocks the following factors are of importance:

(i.) *Refractoriness.* — Test-cones cut from blocks shall not be more fusible than Cone 29.

(ii.) *Porosity.*—The volume porosity of flux-line blocks should not exceed 22 per cent, and of other blocks should not exceed 25 per cent.

(iii.) *Texture.*—The texture of the blocks must be uniform, and only in the case of large blocks should any dark core be permissible. There must be no holes, flaws, or crevices, and the surfaces should be plane so that the blocks may be walled together without appreciable joint space.

(iv.) *Burning.*—Test pieces cut from blocks and heated to 1400° C. for two hours should not show, on cooling, a greater linear contraction or expansion than 2 per cent.

(v.) *Crushing Strength* should not be lower than 1600 lbs. per sq. in., the test being made on a properly prepared 4-inch cube.

The laboratory testing of the probable durability of tank blocks, apart from the measurement of definite physical properties, is a difficult matter. There is at present no single test which can be relied on to determine durability. The resistance to the corrosion of a particular batch or glass may be examined by cementing a large crucible, from which the bottom has been removed, to the face of the block and melting the batch in it. Repeated filling and emptying is necessary; the block is then fractured and the depth of corrosion and penetration measured. Actual immersion of large cubes cut from blocks in molten glass for a week or two gives indications of value. Rees [1] has critically discussed the Provisional Specifications for Tank Blocks prepared by the Society of Glass Technology, and concludes that the data asked for in the specification, together with the indications of tests such as

[1] *Trans. Soc. Glass Tech.* vi. 181.

those referred to above, should enable the glass manufacturer to reject unsuitable material.

There is a general tendency at the present time towards the use of smaller blocks, particularly at the flux line, because of the greater certainty of obtaining a close texture and uniform burning. The following are analyses of blocks which have given satisfactory service with both salt-cake and soda-ash batches in high-temperature tank furnaces :

	Per cent.	Per cent.	Per cent.
Silica	56·32	64·69	67·41
Alumina . . .	36·02	30·41	27·76
Iron oxide . . .	2·94	1·84	1·72
Titanium oxide . .	2·12	1·16	1·04
Lime	0·61	0·51	0·52
Magnesia . . .	0·42	0·37	0·21
Potassium oxide / Sodium oxide	1·48	0·96	1·22
	99·91	99·94	99·88
Volume porosity .	21%	19%	21%
Linear after-contraction at 1400° C.	1·8%	1·2%	1·0%
Refractoriness . .	Cone 33	Cone 30	Cone 29

Blocks of higher silica content may give satisfactory service with soda-ash batches, but the superior resistance to corrosion of blocks properly manufactured from clays containing only small proportions of free silica indicates the desirability of their selection. With such clays the resistant skin of sillimanite is more readily formed and maintained as interaction between block and glass occurs ; solution or corrosion of the block is correspondingly retarded. Apart from chemical composition, the two factors having the greatest influence on durability are porosity and uniformity of texture. Uniform wear is unlikely if the texture is uneven, or if cracks, holes, or flaws are present which permit entrance of the molten glass to the interior of the block.

When tank blocks are first put into service, the furnace should be raised to a high temperature before any glass or batch is filled in.[1] The absorption of molten glass by porous tank blocks is a frequent cause of rapid destruction, as interaction between glass and clay will occur within the block at temperatures below the melting-point of the glass. J. W. Cobb [2] has shown that silica and fluxes such as lime interact at temperatures as low as 700°-800° C. Low-temperature reactions of this character occurring within the tank block will very considerably reduce its life ; the coefficient of expansion of that portion of the block will be materially altered with the probability of the spalling away of the face of the block and a consequent further increase in the rate of wear as the fresh porous clay is exposed to the glass. Some of the wear of tank blocks below the metal level may be due to mechanical and not chemical corrosion. The flow of glass in the tank will depend upon several factors, such as temperature and viscosity, heat distribution, rate of melting and withdrawal of glass, shape of tank, location and size of dog-holes in fixed bridge tanks, but, in general, a block composition and structure which favours resistance to chemical corrosion will also favour resistance to the mechanical corrosion caused by the moving glass.

The preparation of a resistant face by coating tank blocks with mixtures such as are used in lining pots has not, up to the present, been successful, but it presents a wide field for experiment.

§ (19) Preservation of Tank Blocks by Cooling.—The prolongation of the life of furnace linings by cooling the external surface has been demonstrated by the application of water-cooling devices to the blast furnace and the open-hearth furnace. During recent years cooling devices have been successfully applied in glass-tank operation. In a tank furnace with fixed bridge, cooling of the bridge blocks is essential, as the normal cooling by radiation is so much less than in the side walls ; for the side walls and dog-house also, cooling is beneficial and will increase the life of the blocks. The following cooling methods are in use :

(*a*) Cold air—blown by fans or delivered from a compressor through nozzles.

(*b*) Moist air—nozzles introducing steam into the air-duct in sufficient quantity to saturate the air.

(*c*) Steam jets impinging on the blocks.

(*d*) Water-cooling.

For bridge-cooling, air or steam jets are satisfactory, as the cooling obtained is sufficient to protect the blocks without impeding the flow of metal through the throat. If the cooling is excessive (or in the case of water-coolers, inefficiently designed) the metal in the throat may be frozen and the flow into the working end of the furnace impeded or even stopped. Excessive cooling may also induce local devitrification and so cause " stones " in the metal. The greatest cooling effect is obtained by water-cooling ; it is obviously important that there shall be good contact between the cooler and the tank block. The temperature gradient through the blocks may be so materially altered as to maintain a skin of frozen glass on the internal surface. The cost of the installation and maintenance of cooling devices must be set off against the reduced consumption of blocks and the fuel consumption in the furnace. A limit to the

[1] See also § (13).

[2] *Jour. Soc. Chem. Ind.*, 1910, xxix. 335.

expenditure in cooling is thus soon reached. In glass-tank operation air or steam cooling is generally adopted; sufficient cooling is obtained, and the cost of installation and maintenance is less than that of water-cooling devices. Over-cooling of furnace walls will not only increase fuel consumption but will also cause defective glass, since devitrified glass may be drawn in by the glass flow and may be incompletely dissolved by the molten glass. It may thus pass through into the cooler working end of the furnace, and extensive devitrification may start from those nuclei.

§ (20) Accessories.—Where fully automatic machines are employed in glass-making, the feeding device which may be necessary is an important unit. Such devices may necessitate the employment of refractory tubes, troughs, or spouts which must be highly resistant to the solvent action of the glass and to the abrasive action of the stream of glass; ability to withstand temperature changes is also in many cases necessary. Aluminous clays admixed with a large proportion of angular hard-fired grog will give the most resistant bodies under such conditions. The porosity of the body when fired should not be higher than 20-25 per cent. In some cases good results have been obtained by the use of bodies of porcellanic type.

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Refractory Oxides. See "Refractories," § (44).

Refractory Oxides, Fused, Preparation of. See "Furnaces for Laboratory Use," § (5) (i.).

Resistance Alloys. See "Alloys, Some Special," § (2).

Resistance Furnaces, carbon or graphite. See "Furnaces for Laboratory Use," § (3).
Contact. *See ibid.* § (3) (*d*).
Granular. See *ibid.* § (3) (*c*).

Resister Furnaces. See "Furnaces, Electric," § (2) (iii.).

Rocks, Plastic Deformation of. See "Solids, The Flow of."

Rolling: the reduction of metal by passing through a pair of rolls. See "Metals, Thermal and Mechanical Treatment of," § (6).

— S —

Season Cracking: apparently spontaneous cracking of metals (especially brass) occurring after completion of manufacture, sometimes after considerable lapse of time. Such cracking is the result of the prolonged action of sufficiently severe stresses, which may be externally applied, but are usually internal, consequent upon unequal cold-working. See "Metals, the Relations of Strain and Structure," § (7).

Segregation: the unequal distribution of the various constituents in different regions of a mass of solid metal or alloy. See "Metals, Thermal and Mechanical Treatment of," § (3); "Metals, Defects and Failure of," § (2).

Series System of Arranging Cells in Copper Refining. See "Copper, Electrolytic Refining of," § (2).

Sherardising: production of a coating of zinc on steel by heating it in contact with zinc powder. See "Metals, Thermal and Mechanical Treatment of," § (12).

Shore Hardness Test measured by the Shore Scleroscope, which consists of a tube, down which a small steel weight with a hardened point is dropped on to the specimen to be tested. The height of rebound is taken as the measure of hardness. See "Steels, Special," § (2).

Shuts, Cold: defects in ingots or castings due to failure of successive portions of metal to coalesce before solidification. See "Metals, Thermal and Mechanical Treatment of," § (2).

Silica, Physical Properties of. See "Refractories," §§ (32)-(36).

Silica Bricks. See "Refractories," § (37).
Properties of. See *ibid.* § (38); also "Refractories used in Glass Making," § 2.

Silica for Furnace Tubes. See "Furnaces for Laboratory Use," § (2).

Silicon, existence in steel. See "Iron-carbon Alloys," § (14); also "Steels, Special," § (22).

Silicon Alloys. See "Steels, Special," § (48) (iv.).

Silicon Carbide. See "Refractories," § (53).
Manufacture of. See "Furnaces, Electric," § (5) (ii.).

Sillimanite. See "Refractories," § (52).

Silver-copper Alloys. See "Alloy Systems, Typical," § (8).

Slip Bands: fine lines, in reality minute steps formed on cut, polished, or natural surfaces of crystals, as the result of plastic deformation, to which the crystals accommodate themselves by a process of sliding or slip, which takes place on certain crystalline planes. See "Metals, the Relations of Strain and Structure," § (1).

Softening-point of a Refractory Substance. See "Refractories," § (2).

Its measurement. See *ibid.* § (3).

Solid Solubility of Alloys. See "Metals and Alloys, Micro-structure of," § (6).

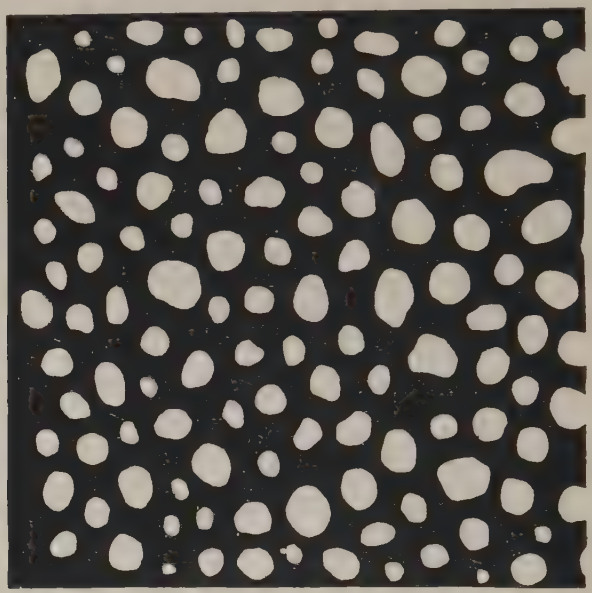

Fig. 1.—Perforation of the film by small holes.

Solid Solution: a solution or intimate mixture of one metal in another when solid, forming an alloy corresponding to the state of solution when the metals are liquid, the alloy crystallising while still remaining a solution. Each of the crystals formed ultimately attains the same composition as the molten liquid from which it was deposited. See "Metals, the Relations of Strain and Structure," § (10).

SOLIDS, THE AGGREGATION OF

§ (1) Effects of Surface Tension.—The forms assumed by solids in the earlier stages of their aggregation have been the subject of many conflicting experiments, and much diversity of opinion exists as to whether the minute solid aggregate which first forms is crystalline and possesses a crystalline outline, or whether the aggregate is spherical with its boundaries controlled by the force of surface tension.

The view that the crystalline force, under certain conditions, may be held in check and actually overpowered by surface tension, was put forward by Sir George Beilby in 1903 (1). His conclusions were drawn from critical observations with the microscope of the surface structure of metals in their most attenuated form, and from the effects of heat and of solvents on thin films, and on surface films of metals and other crystalline solids. These observations show conclusively that considerable molecular mobility and rearrangement is brought about at a temperature very much below the melting-point of the metal.

The mere fact that a certain amount of freedom was imparted to the molecules by heat was not surprising in view of the well-established facts of segregation and crystal growth in masses of metal at temperatures much below their melting-point. That this freedom takes place under conditions which lead the solid molecules to behave like liquid molecules was, however, both new and suggestive.

His experiments demonstrate that the effects of heat, in the annealing of thin films of metals, is to confer on the solid molecules a state of freedom which permits their mutual attraction to draw them together into granular or drop-like forms in a manner identical to that of a thin film of a viscous fluid.

The illustrations, *Figs.* 1, 2, 3, and 4, are

diagrams showing four stages in the aggregation of a thin oil film on water: first, the perforation of the film by small holes; second, the enlargement of these holes and the gathering up of the film into mere ridges between them; third, the dividing of the ridges into separate pieces, and fourth, the final state in which the oil is gathered into isolated discs or flattened droplets. Similar forms are obtained during the annealing of thin metallic films at temperatures considerably below the softening-point of the metals. *Figs.* 5 and 6

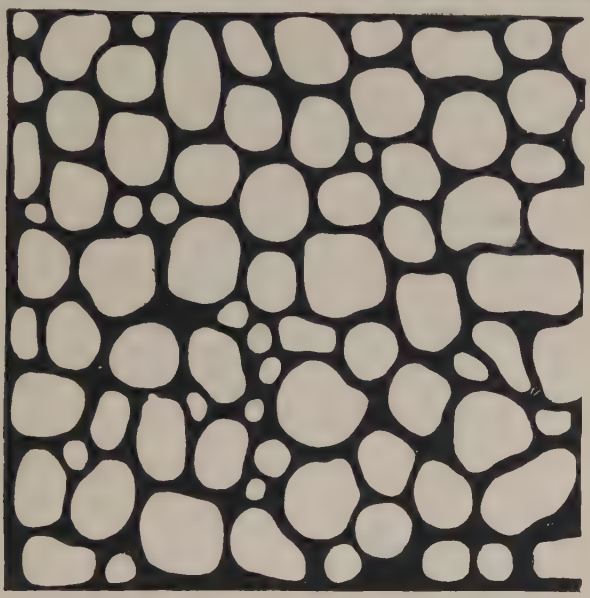

FIG. 2.—Enlargement of the holes and the gathering up of the film into ridges between them.

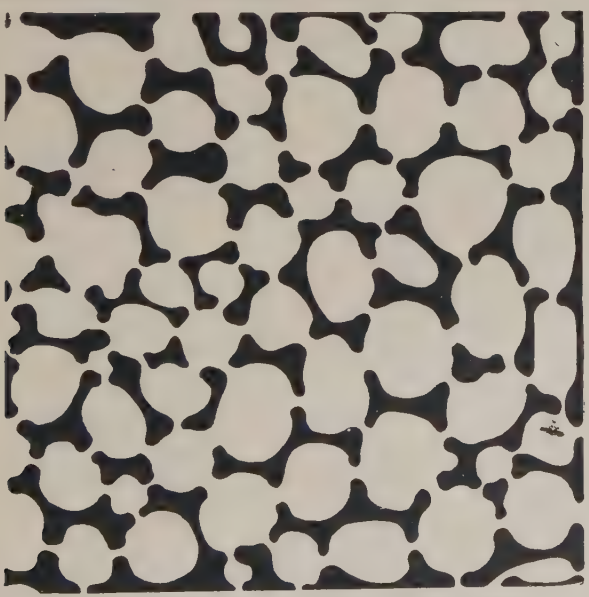

FIG. 3.—The ridges break across and tend to draw up into rounded forms.

are photo-micrographs of annealed gold films. *Fig.* 5 was a thick film. The dark patches in the photograph were deep green and the light patches a pale pink by transmitted light. *Fig.* 6 was a much thinner film. During the annealing the films have aggregated in a manner analogous to that of a viscous fluid.

Another agency by which this freedom may be conferred upon the surface molecules is the application of solvents or partial solvents. The molecular mobility which occurs at the moment of the partial solution of a solid surface, or on the separation of a solid from solution, are occasions which may be seized by the forces of surface tension, with the result that the forms of structure which are due to these forces are found both on surfaces which have been slightly etched by solvents, and in solid films which have been deposited from solution. At the surfaces of solids and liquids alike, these potential forces are always present and ready to take advantage of any increase in the mobility of the molecules to impress their characteristic forms of aggregation upon them.

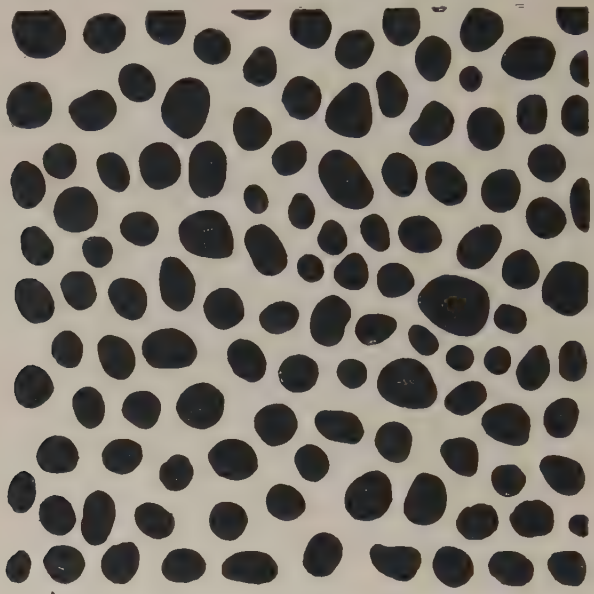

FIG. 4.—The film completely resolved into isolated discs.

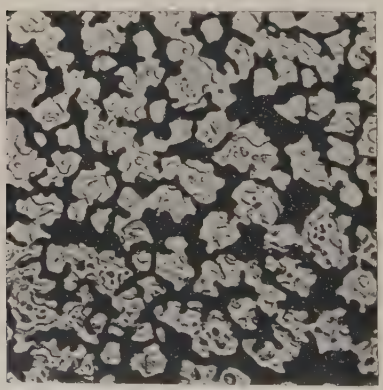

FIG. 5.—Gold film-phosphorus reduced—annealed by heating on glass. The dark patches were deep green, and the light patches pale pink by transmitted light. × 440.

FIG. 6.—The thinnest part of the same gold film. × 440.

This is well illustrated in the behaviour of two such widely different substances as gold and glass when slightly etched with chlorine water and hydrofluoric acid respectively (*Figs.* 7 and 8). The surface aggregation on the glass is so remarkably like that developed on the gold that it would be very difficult to distinguish the two photographs when looked at apart, while the resemblance of these surfaces to that of a thin film of a viscous fluid and to the annealed gold film shown in *Fig.* 6 is very striking.

FIG. 7.—Surface of a plate of pure gold after lightly etching with chlorine water. ×1000.

This granular structure due to surface tension can be observed in solids under many and varying conditions. Films of oxide or sulphide which form on metal surfaces show it very markedly. It can be observed in thin films of metals deposited either chemically or electrolytically, and also in precipitates formed in very dilute solutions. The thin film, which forms at the surface of contact of the two reagents, breaks up into minute particles. Their pedetic movement leads to their agglomeration into larger granules which become centres of attraction to the smaller particles and grow by their absorption. Till the granule has reached a certain size and mass it shows no indication of crystalline shape or structure, and its form remains under the control of surface tension rounded and granular. When a certain size is reached the crystallic force begins to assert itself and to overpower surface tension, and the rounded form begins to develop faces and angles, till finally a well-developed crystal is produced (2). Again, in the separation of solids directly from the gaseous state, such as magnesium oxide, zinc, ammonium chloride, and smoke aggregates of all kinds, the granular and rounded forms are assumed by the molecular aggregates. Microscopists are familiar with the forms which are seen when very thin films of salt solutions are allowed to crystallise on a glass slip. If the film of solid salt is below a certain thickness, the forms assumed are purely those due to surface tension. As the thickness of the film is increased, the crystallic force overpowers the surface tension and the deposit becomes more and more crystalline. Observations by Beilby (3) have shown that there is a definite limit for each substance below which the crystallic force is completely controlled by surface tension.

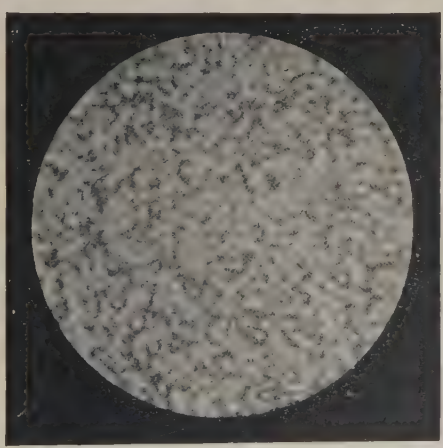

FIG. 8.—Surface of fire-glazed glass slip after lightly etching with hydrofluoric acid gas mixed with air. ×1000.

It follows from these observations that a freely suspended aggregate of solid molecules will take the spherical form if its surface is sufficiently large compared with its mass. A globule will only take the external form of a crystal when its mass becomes large enough to permit the crystallic force to overpower surface tension.

§ (2) INITIAL SHAPE OF AN AGGREGATE.—In the well-known case of liquids, when free from the influence of external forces, a drop will assume the shape in which its potential energy is a minimum, *i.e.* the shape in which the area of the surface is a minimum, and consequently the drops will be spherical. In a similar way a solid crystal tends to assume the shape in which its surface energy is a minimum, but since the different faces of a crystal have different capillary constants, crystals do not assume the spherical form, but assume a shape in which the total surface

has a minimum area in keeping with the crystalline structure. From this it follows that when crystals of various sizes are placed in contact with a saturated solution of the same substance the smaller crystals tend to disappear into solution and are redeposited on the larger crystals. In the case of aqueous solutions this has been worked out quantitatively, and used as a means to calculate the surface tension between a solid and a liquid.

This effect has also been observed in solids. The researches of Neville and Heycock (4) have shown that, even in the solid state, the larger crystals grow at the expense of the smaller, and eventually swallow them up. The range of the crystalline force therefore widens as the mass of the crystal is increased, while the range of molecular force remains constant. It is possible, therefore, that the average size of the granules in solids may result from the establishment of a state of equilibrium between these rival forces (5).

The peculiar crystals of the oleates, which are soft enough to be deformed by slight pressure, furnish a striking example of a case where the directive force is practically balanced by that of surface tension. In potassium oleate, for instance, the existence of the directive force is shown by the assumption of elongated and somewhat rounded forms of the crystals, which, when examined optically, are found to belong to the tetragonal system. If two of the oval forms are brought into contact with their longer axis at right angles to one another they do not coalesce, and their forms are unchanged. If, however, the crystals are placed in contact with their longer axis parallel, deformation takes place and the crystals begin to coalesce, and finally one is absorbed by the other until a single crystal is obtained which resembles the originals in all respects. The union is obviously due to surface tension, and takes place in a similar manner to the union of two drops of a liquid and is an extreme instance of the condition which probably prevails in many substances during the process of solidification.

The investigations of Lehmann and Quincke on the forms produced in colloidal substances due to surface tension abundantly bear out the conclusions of Beilby. More recently the subject has been further investigated by Tammann, whose results confirmed the above. He has been able to express his conclusions in mathematical form, and these he has confirmed by the determination of the tensile strength of metallic films at high temperatures (6).

An attempt to decide whether the minute solid aggregate, which first forms in the crystallisation of salts, has a globular or crystalline outline, was made by Richards and Archibald (7). The method which they adopted was to study growing crystals by the aid of instantaneous photography. They worked chiefly with inorganic salts, and the photographs show that the aggregate, from the first moment that it is able to produce an effect on the photographic plate, has a distinct polyhedral outline.

The X-ray interference method employed by Debye and Scherrer in the morphological investigation of finely divided substances has recently been applied in an attempt to determine the size and structure of the minute aggregations in typical inorganic and organic colloids (8). Colloid silver and gold are found to be definitely crystalline; the interference figures obtained in the examination of these substances corresponds with a space lattice, which is identical with that indicated by the observations on macroscopic crystals of the metals. The characteristic space lattice is indeed shown by gold particles, which are too small to be observed by the ultra-microscope. Typical organic colloids, such as albumen, gelatine, cellulose, and starch, afford no evidence of internal structural regularity, and it is probable that the colloid particles of these substances consist of individual molecules or of irregularly oriented groups of molecules.

Diesselhorst and Freundlich (9) have shown, by experiments on the relationship between the Tyndall effect and the shape of colloid particles, that the colloid particles of gold and silver are spherical, while in some other substances, such as graphite and ferric hydroxide, disc-like particles have been distinguished, while in some other sols rod-like forms occur. These results agree with those obtained by microscopic and ultra-microscopic research.

These experiments on colloidal gold particles suggest that the minute aggregates have their boundaries controlled by surface tension, while within this outer spherical skin the individual molecules possess a regular orientation, and it is only when the aggregate increases sufficiently in mass that the crystallic force is able to overpower the surface tension and the aggregate begins to assume a crystalline outline.

The aggregation and solidification of metals and alloys have been extensively studied by many workers, and a very complete summary of the subject has recently been published by the Institute of Metals (10).

§ (3) The Foam Theory. — Quincke has put forward an hypothesis which is based on the fact that when two liquids, which are only partially miscible, are shaken together, and when one of the liquids is in large excess, the other may become distributed in such a way as to form thin cell walls, enclosing the drops of the first liquid. Such a structure is known as a foam. In

the case of the solidification of metals the first step towards crystallisation occurs in the liquid state, and consists in the segregation of the pure substance and the throwing out of any eutectic which may be present. In these two liquids differences in intrinsic cohesion cause the pure substance to aggregate in spheroidal masses, around which the eutectic forms in bubbles or "foam-cells." The spheroids of pure substance, being isolated from each other by the foam-cells, are free to develop each their own crystalline orientation. This may occur while they are still liquid, or it may only occur on solidification; but in either case the result is the same, and the spheroids solidify as little sacs of uniformly oriented molecules. On this view the coalescence of small grains to form larger ones during the process of annealing indicates the general tendency of foams to become coarser in structure. Other evidence in favour of this hypothesis is found in the corrosion of the boundaries of the crystal grains by etching reagents, pointing to a difference of composition between the foam cells and their contents, and from the increased volatilisation at the boundaries when metals are heated to a high temperature *in vacuo*.

From a general review of the researches on the aggregation of solids from their molecules the balance of experimental evidence seems to favour the view that there is a certain size of the aggregate up to which its form is controlled by the force of surface tension, although the individual molecules in the aggregate may possess crystalline orientation, and it is only after this point is passed that the crystallic force comes into full play and the aggregate begins to assume a definite crystalline outline.

W. D. H.

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SOLIDS, THE FLOW OF

§ (1) HISTORICAL.—Within the last half-century the structure and properties of solids have been the subject of much experimental research, and the older idea that the solid state was a state of inertness and repose has had to give way before the rapidly accumulating proofs that the molecules of the solid state possess activities of a most marked and varied nature.

Tresca was among the first to demonstrate that solids such as the metals could be made to behave like highly viscous fluids under the influence of pressure, and that they could be "squirted" through openings under pressure to form continuous wires. Spring (1), in his researches published in 1880, attacked the problems of the conditions which determine flow in solids. His experiments were made on various substances at high pressures and at the ordinary atmospheric temperature. Among the many results obtained by him lead filings were compressed into a uniform block, and finely powdered bismuth was converted by a pressure of 6000 atmospheres into a uniform crystalline block. In these earlier experiments Spring attributed the welding or flowing mainly to pressure, that is, to the close approximation of the particles brought about by pressure. In a second series of experiments (2) in 1887–88 he attempted to show that chemical reactions could take place between substances in the solid state which were simply in contact with each other, and that atomic or chemical interchange could take place between solids. These researches of Spring brought to light another closely related property of solids, namely, "diffusion." This study was taken up by the late Sir William Roberts-Austen (3), who was able to determine the rate of diffusion of gold and platinum into lead, both in the liquid and the solid state.

The many researches of Sir George Beilby supply fresh proofs of the mobility of the solid molecules, while they, for the first time, enable us to define more closely some of the conditions of this mobility and the limitations under which it takes place. His observations are based chiefly on the flow of solids under mechanical disturbance, and have led him to formulate a theory of polishing which explains the known facts with remarkable clearness. Herschel (4), who was regarded as one of the first authorities on this subject, considered polishing as only a still finer abrading action, and that it consisted in grinding down large asperities into smaller ones by the use of hard gritty powders.

In a paper on Polish (5), the late Lord Rayleigh suggested that the operation may be a molecular one, and that "in the polishing of a soft substance such as copper, it is possible that material may be loosened from its original position without becoming detached. In such a case pits in the surface may actually be filled in by which the operation would be much quickened," but he states that nothing suggestive of this effect has been observed in experiments upon glass, and the completion of the process consists in rubbing away the whole surface down to the level of the deepest pits.

§ (2) BEILBY'S RESEARCHES.—On the other hand, the researches of Beilby (6) show con-

clusively that the production of a polish is due to the molecular flowing of the surface being polished, and that to obtain a perfect polish it is not necessary to wear down the surface to the level of the deepest pits, but that these pits are actually covered over by a thin layer of the flowed surface material (7). He has also shown that flow takes place, although only to a small depth, on even the hardest crystalline substances. This flowed layer on polished substances differs from the original material in that it is vitreous, and not crystalline. It is a structureless material strongly resembling in its behaviour a highly viscous fluid. The accepted theory of polishing as formulated by Beilby (8) is that "in all substances if they are sufficiently homogeneous to be polished at all, the fundamental principles on which polishing depends are absolutely identical and that the polished surface on a solid substance is as truly due to the presence of a surface tension skin as is the surface of a liquid." From this it is obvious that the keystone of the theory is the instantaneous liquefaction and solidification of sheets of molecules during the mechanical deformation caused by the polisher. It is due to the almost molecular fineness of the powders used in polishing that the necessary molecular contact over comparatively large areas simultaneously can occur, when something like a continuous sheet of molecules of the polishing and the polished surfaces are in contact. This disturbed molecular layer retains its mobility for an instant, and before solidification is smoothed over by the action of surface tension, thus producing the liquid-like surface which is the necessary condition of a perfect polish.

FIG. 1.—Crystalline antimony after rubbing on fine emery paper. ×775.

FIG. 2.—The same after polishing on rouged leather. ×775.

FIG. 3.—The same after partial etching with KCy. ×775.

The formation of this flowed layer is well shown on the surface of such a brittle metal as antimony. If a surface of an antimony crystal, which has been first grooved by rubbing on fine emery (*Fig.* 1), is lightly polished on rouged wash-leather across the emery grooves, the process of the formation of the flowed vitreous layer can be conveniently watched by examining it from time to time under the microscope. The flowed material is seen to gradually creep over the edges of the grooves and to bridge over the finer ones, and if the operation is continued even the deeper scratches are easily covered up in this way (*Fig.* 2). The whole then presents the appearance of a perfectly smooth

polished surface. That the scratches and pits are only covered and not removed is readily seen on etching with a suitable reagent, which dissolves the film and exposes the original grooved surface (*Fig.* 3). This mobile film can be carried across the smaller furrows and pits during polishing without any support from below. *Fig.* 4 shows the pits on a polished antimony surface in process of being covered over with the flowed material. The next two figures illustrate this point more completely. *Fig.* 5 is a high-power photomicrograph (×1800) in natural colour of pits on a polished copper surface. These have been completely flowed over with the polished layer. The pits are covered with a blue film, but show patches of red on the blue. *Fig.* 6 shows the same surface after the film has been removed by etching. On comparing these two photographs it will be seen that the red patches in *Fig.* 5 correspond with the spots of light reflected from the concave surfaces of the uncovered pits shown in *Fig.* 6, so that these pits must have been practically empty when they were covered by the film, and that the film during its flow was quite unsupported from below.

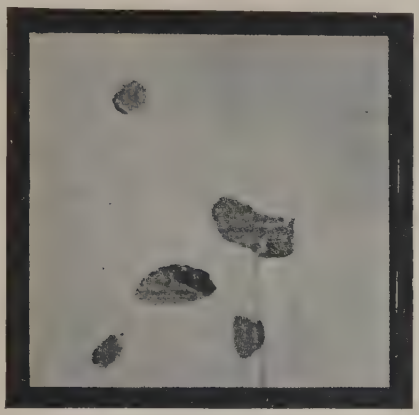

FIG. 4.—The same, showing pits covered with film of flowed metal. ×775.

The flow due to mechanical disturbance may take place throughout a brittle crystalline mass and not merely at the surface. If a small crystal of antimony is struck with a hammer, the brittle fragment, instead of flying into powder under the blow, is spread out into a thin plate as any malleable substance would be (*Figs.* 7 and 8).

The extremely slight mechanical treatment which will suffice to cause molecular movement and flow on the surface of a highly crystalline substance is seen in a remarkable way in the behaviour of calcite (9). If a part of a freshly cleaved surface of calcite is etched with a drop of dilute hydrochloric acid, no new structures or markings are visible even under the most critical microscopic examination. If the cleaned face is stroked lightly a few times with the forefinger covered with a piece of soft chamois-leather and then examined under the microscope, the surface is still smooth and unmarked by the stroking, but if etched with

FIG. 5.—High-power photo-micrograph in natural colour of pits on polished copper surface, showing film covering pits. ×1800.

FIG. 6.—The same with film removed by etching. ×1800.

a drop of dilute hydrochloric acid and then examined, furrows and ridges will be observed

FIG. 7.—Microscopic crystal of antimony.

running in the direction of the finger strokes (*Fig.* 9). This skin gives unmistakable signs that it has passed through a state in which it must have possessed the perfect mobility of a liquid. In its final state it possesses distinctive qualities which differentiate its substance very clearly from that of the unaltered substance beneath it. It is, for instance, much harder, and, even when formed on the surface of a crystal on which the hardness varies in different directions, its hardness is the same in all directions. This skin is also more readily attacked by solvents, consequently it was found possible to dissolve the skin off in steps or stages and thus to gain an insight into the history of its formation. These results of etching show that the mechanical disturbance caused by the polishing agent has penetrated to a depth of 500 to 1000 $\mu\mu$. At this depth the disturbance consists mainly of the deeper scratches or furrows which have been ploughed through the thin lamellae of which the crystal is built up. The ploughing has so completely flowed the crystalline substance that the scratches and furrows have been healed over so that no trace of them is visible from the surface. As the surface is approached the furrows become finer and more numerous, till at a distance of 100 $\mu\mu$ from the surface they disappear and the action of the solvent only discloses very fine flow lines similar to those observed in polishing metals. In the 50 to 100 $\mu\mu$ at the surface there is no trace even of the broken-up lamellae, and the appearance is absolutely homogeneous and vitreous like a coating of varnish or enamel. In metals (10) the general physical and electrical properties of the flowed vitreous layer have been found to differ from that of the original metal. The electrical conductivity of the flowed metal is lower than that of the unflowed or annealed. There is also a difference in electric potential between a metal in the two states, and it has been found that the heat of solution of the flowed metal is greater than that of the metal in the ordinary annealed state.

§ (3) METALLIC STRUCTURE.—The discovery that layers of a solid many hundreds of molecules in thickness can have the mobility of the liquid state conferred on them by purely mechanical movement, opened up a new field of inquiry into the internal structure of metals which have been hardened by cold working. As a result of this inquiry

FIG. 8.—The same made to flow by a single blow from a small drop-hammer.

a new theory of the hard and soft states in metals was proposed by Beilby, which explains the facts very completely (11). According to his theory hardening results from the formation at all the internal surfaces of slip or shear of mobile layers similar to those produced on the outer surface by polishing. These layers only retain their mobility for a very brief period and then solidify in the vitreous state, thus forming a cementing material at all surfaces of slip or shear throughout the mass. This material is harder and more resistant to stresses than the original metal. Slipping is easy so long as fresh moving surfaces are available, but when all the available crystalline material becomes encased in the hard and unyielding flowed material plasticity under these particular stresses comes to an end. This theory, therefore, for the first time supplied the needed explanation of the passage of a metal through a highly plastic stage to a state of hardness and tenacity much greater than it originally possessed.

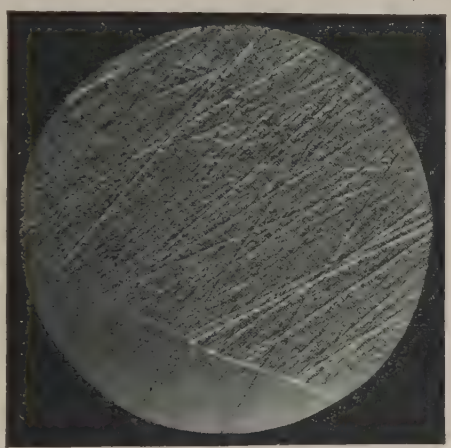

Fig. 9.—Polished Iceland spar showing etched and unetched surface. ×215.

The most significant feature of the observations on which the arguments for this theory are based is the evidence they supply of the mechanical breaking down of the crystalline into the vitreous state, and of the existence of an intermediate mobile condition of the molecules at the internal surfaces at which movement is taking place. This mechanically produced change has been found not only in metals but in solids of all kinds. Quartz, agate, calc-spar, glass, graphite, sulphur, ice, gelatin, and a great variety of crystalline salts, organic and inorganic, have been experimented with, and all without exception show the same effects. Neither deformation nor polishing can take place without this condition of flow. The discovery that the conversion of the crystalline into the vitreous state through the mechanical displacement of the molecules is a universal process, appears to give to the relation between the two states a new and wider significance. The passage of the vitreous back to the crystalline through the agency of heat accounts for the restored plasticity in metals brought about by annealing. In all solids there is a definite temperature below which the vitreous condition is stable. In the case of metals it has been shown that the stability point is situated a long way below the solidifying point. Gold, silver, and copper, for example, all pass from the vitreous to the crystalline state between 230° and 290° C., while their solidifying points are in the neighbourhood of 1000° C. The observations show that in a number of substances, although the vitreous state is thermally unstable above its stability point, yet below that point it is at least as stable thermally while it is mechanically more stable than the crystalline state.

Experiments on the flow of calcite and of quartz have a very direct bearing on the plastic deformation of rocks (12). The researches of Adams and Nicholson (13) on the "Flow of Carrara Marble" supply indirectly a proof of this theory of the flow in solids. The remarkable ease with which calcite can be made to flow under slight disturbance would at first sight appear quite incompatible with the limited plasticity exhibited by marble, even under the enormous stresses used in their experiments. But the whole subject becomes more comprehensible when it is recognised that the effect of any deformation, however slight, is to break down the crystalline into a mobile state at all surfaces where movement takes place, and that this mobile state is immediately succeeded by the vitreous state, which actually cements the moving surfaces together, and this material being harder and more unyielding than the original causes the mass to become more rigid and to offer a greater resistance to the deforming stresses.

§ (4) Crystalline Powders.—The greater solubility of the vitreous material produced by flow in crystalline solids bears on the question of the increased solubility of crystalline substances in the form of a fine powder (14). It has been suggested that the greater solubility of small crystals as compared with large is due to their greater surface energy, and the further conclusion has been drawn, that the greater solubility of a substance in the form of a powder is due to the same cause. While this suggestion may be justified

up to a point, it is clear that in many cases there is a difference in the solubility of the two states, the vitreous and the crystalline, which is entirely independent of the outward form or mass of the substance. Therefore, as any powder which has been obtained from a crystalline substance by grinding must, from the nature of that operation, be to a considerable extent in the vitreous condition, its greater solubility will probably be due to the existence of this material.

The operation of grinding a crystalline substance to powder does not simply consist of its mechanical reduction to finer and finer crystalline fragments, but it necessarily involves the partial production of the vitreous state (15). A finely powdered substance is vitreous, not because of, nor in proportion to, the mere fineness of its subdivision, but because of the extent to which the transformation from the crystalline state has been effected by flow during grinding. If the grinding takes place at a temperature below the stability point for the substance, the powder will remain in the vitreous condition.

When a crystalline powder is formed into cakes or tabloids by compression, even when the transformation into the vitreous state is incomplete, the cementing material is vitreous and has been formed by flow at the rubbing surfaces of the crystalline grains.

One striking point brought out by the observations of Beilby (16) is that it is not possible by mechanically produced flow to break down the crystalline structure so completely that the metal substance should be entirely converted into the vitreous state. Even such drastic treatment as wire-drawing and gold-beating only results in a partial conversion of the crystalline metal into the vitreous form.

The co-existence of the two states in the same mass of metal explains the variety in the texture of specimens of pure metal which have been subjected to different methods of working. In hammering, the crystalline aggregates are flattened and spread out, and with their covering films of the hard vitreous material may form a laminated or flake-like structure. In rolling or wire-drawing these flakes are elongated longitudinally, thereby producing a more fibrous structure. The increased rigidity of the hardened metal results from this partitioning up of the whole mass by thin rigid cell-walls, which enclose and protect their contents of the plastic material from further deformation and transformation. When a greater stress is applied to the hardened mass, the rigidity of the cellular structure has to be overcome before further yielding can take place. When this structure breaks down, the plastic state which is thereby reached is set in motion and forms itself into a new set of protecting partitions. This accounts for the immediate and marked increase of rigidity which results from the transformation of a small amount of crystalline into vitreous material. W. D. H.

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SOLIDUS in equilibrium diagram. See "Alloys, Constitution of," § (1) (v.).

SOLUBILITY of two metals in the solid state. See "Metals and Alloys, Micro-structure of," § (6).

SORBITE: a constituent of steel. See "Metals and Alloys, Micro-structure of," § (7); "Iron-carbon Alloys," § (10).

SPECIFIC GRAVITY OF STEELS, effect of composition on. See "Steels, Special," § (5), Table 6.

SPECIFIC HEAT of pure iron. See "Steels, Special," § (7).

SPECIFIC VOLUME in relation to composition of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (5).

SPHEROIDISING PROCESS in steel. See "Iron-carbon Alloys," § (10).

SPIRAL FURNACE, GRAPHITE. See "Furnaces for Laboratory Use," § (3) (*b*).

SPRING STEELS: steels with high elastic range, free from brittleness, as used in railway and automobile springs. Analysis. See "Steels, Special," § (47) (iv.), Table 19.

STAINLESS STEEL, contains 12 to 14 per cent chromium. Temperature, tensile strength, etc. See "Steels, Special," § (4) (B) (i.), Table 5.

STEEL. See "Iron-carbon Alloys," § (6).

Electric furnaces for manufacture of. See "Furnaces, Electric," § (4) (v.).

Effect of rapid cooling on. See "Iron-carbon Alloys," § (10).

Effects of hot work on. See *ibid.* § (9).

Effects of cold work on. See *ibid.* § (9).

STEEL AND IRON, elastic properties at high temperatures. See "Steels, Special," § (4) (B) (ii.).

STEEL CASTING, result of reheating. See "Iron-carbon Alloys," § (8).

STEELS, SPECIAL

I. General Considerations

§ (1) Influence of Varying Composition.—The engineer, in the application of knowledge gained by the physicist and himself, is limited by the properties of his materials. Particularly is this so in regard to iron and steel, and the object of this article is to indicate what has been done to develop special steels for the furtherance of engineering progress in different fields. It may be observed that during the last decades metallurgical developments incidentally have inspired developments in engineering. The development of the mass production of steel by the Bessemer, Siemens, and subsequent processes rendered modern engineering possible on the present scale, but it is proposed to devote this article to the compositions and properties of Special Steels, rather than the methods of production.

(i.) *Carbon Steels.*—The carbon steels are dealt with elsewhere, and it is therefore for us to consider the effects of the addition of other elements to the iron-carbon steels or alloys upon the different properties. One does not require to go back more than two or three generations to find wrought iron as still the essential constructional material in this field. The last quarter of the nineteenth century witnessed its replacement by steel, but it is of interest to record that even the quantitative influence of carbon when added to steel in varying proportions was not worked out until the latter portion of last century. Carbon of all the elements has the greatest influence upon the properties of iron, and it will be appreciated that, until its influence was settled, the true value of other added elements could not be determined. The early chemists did, however, conceive the idea of improving iron and steel by alloying other elements, and notable amongst them was Faraday, who actually produced chromium and other alloy steels as early as 1822. It will be appreciated, however, that until suitable analytical methods had been devised to determine the exact composition, as well as microscopic examination for studying the constitution, and suitable means of thermal analysis, and until steels were studied from the standpoint of physical chemistry, the experimental production of special steels was carried on in an empirical manner. Nevertheless, important discoveries were made prior to the birth of metallography.

The "toughness" associated with wrought iron, and hardness associated with cutting tools of hardened carbon steel, were the original outstanding features in the physical properties of iron and steel. To increase the hardness without reducing the "toughness," and to increase the toughness without destroying the hardness, constituted the obvious lines for experiment, and satisfactory achievements were the result. Let us first of all consider the effect of adding gradual increments of carbon content in steel.

In Table 1 will be found the analyses of carbon steels[1] in which the carbon increases from 0·15 to 0·90 per cent. Full mechanical tests also are given, which clearly indicate the influence which this increase in carbon has had in modifying the hardness, ductility, and general mechanical properties of the material.

These tests are all performed upon the steels in the normalised condition. It is not here proposed to discuss in detail the influence of carbon, since that matter forms the subject of a special article elsewhere. It will, however, be seen that as the carbon content increases, the maximum stress in tons per square inch which the material will withstand increases, whilst the ductility decreases. It will be seen that the Izod notched bar test indicates a gradually decreasing absorption of energy during fracture as the carbon increases. The higher carbon steels of the series in very thin sections, as in the case of knives, some forms of tool, etc., may be hardened satisfactorily, but when the section of the material attains any considerable thickness, then quenching in water—which is the most effective method of quenching—does not carry away the heat quickly enough to cause a sufficiently rapid drop in temperature to enable the hardened condition of the material to be retained throughout the mass. It will thus be seen that if we were confined to carbon steels it would not be possible to produce, in heavy masses, parts having the characteristics of hardened and tempered steels. The addition of nickel, chromium, and other elements is particularly valuable, because they facilitate an easy suppression of the carbon change-point and therefore enable large masses to be quenched satisfactorily. If steel is first quenched and then tempered, the resulting mechanical properties, for the same hardness, are generally superior to the properties obtaining in carbon steels in the normalised condition of such hardness. It will be seen, therefore, that the essential feature of alloy steels is the improved mechanical properties for the same hardness, and, incidentally, that steels of much greater strength than ordinary carbon steel can be obtained with satisfactory capacity for plastic deformation still remaining.

(ii.) *Alloy Steels.*—There are several special alloy steels which come in quite a different category, since the addition of the special

[1] W. H. Hatfield, *Proc. Inst. of Automobile Engineers*, April 1920.

TABLE I

Steel.	0·15 per cent Carbon.	30-Ton Carbon.	40-Ton Carbon.	50-Ton Carbon.	0·9-1·0 per cent Carbon.
Carbon, per cent	0·15	0·31	0·45	0·60	0·90
Manganese, per cent	0·30	0·67	0·70	0·69	0·55
Silicon, per cent	0·06	0·14	0·15	0·20	0·11
Sulphur, per cent	0·034	0·048	0·044	0·04	0·036
Phosphorus, per cent	0·018	0·04	0·036	0·039	0·031
Chromium, per cent	Nil	Nil	Nil	Nil	Nil
Nickel, per cent	Nil	Nil	Nil	Nil	Nil
Condition.	Normalised. 900° C.	Normalised. 850° C.	Normalised. 820° C.	Normalised. 810° C.	Normalised. 850° C.
Tensile—					
Elastic limit, tons/sq. in.	14·0	20·05	21·5	27·0	23·16
Yield point, tons/sq. in.	14·0	20·70	22·9	29·16	32·4
Maximum stress, tons/sq. in.	21·4	35·17	41·2	48·60	59·4
Elongation, per cent	45·0	30·5	25·0	22·0	11·0
Reduction of area, per cent	73·56	54·6	47·0	37·9	15·5
Torsion—					
Yield	7·63	14·1	15·6	16·6	18·8
Probable maximum stress	20·95	27·51	29·0	33·3	35·7
Degrees twist	1070	548	434	320	184
Izod, ft.-lbs.	81	33	28	8	2
Arnold reversals	456	444	500	480	352
Stanton blows	1016	1413	1244	1139	264
Sankey, ft.-lbs.	2300	1700	3974	2496	1112
Brinell number	95	156	170	223	286
Shore number	21	27	29	35	40

elements to the alloy gives distinctly different mechanical and physical properties, as in the case of manganese steel, which contains 12-14 per cent of manganese, as a result of which it is non-magnetic, *i.e.* may be in the austenitic condition at ordinary temperatures, has an abnormal capacity for plastic deformation, as shown by the elongation and reduction of area for a given tonnage, and resists wear abnormally; 12-14 per cent chromium steel, which may be, in the hardened and tempered condition, perfectly rust-resisting; and in the case of the "Invar" metal, where the addition of a large percentage of nickel has produced a profound effect upon the coefficient of expansion.

As an instance of the large range of mechanical properties which can be introduced into one given high tensile alloy steel, *Fig.* 1 [1] will be of interest. In the curves is shown the diverse response which a nickel-chromium steel, when hardened and tempered, may be made to give to the various standard forms of mechanical test. Micrographs A to F illustrate changes in structure accompanying the changes in properties.

In the article on the "Iron-carbon Alloys" the iron-carbide diagram has been thoroughly discussed and illustrated, and we must here record that the addition of the various elements in the production of special steels results in a definite change of the position of the lines of the diagram. Although much quantitative work has not yet been carried out into the effect of the various elements on the liquidus and solidus lines, yet it is definitely known that these are substantially modified. With large additions of special elements they are frequently depressed. This is a fact of considerable importance, since the lowering of the solidus line demands most accurate control of the temperature used when the steel is heated for forging and rolling operations. The area of the diagram which marks out the solid solution phase has its boundaries considerably modified; for instance, chromium, by its effect of raising the Ac_1 or carbon change-point, restricts the area, whilst nickel, by lowering the temperature of this phase change, extends the area. Again, take the elements tungsten and molybdenum; their presence in the extremely complicated steels which will be dealt with results in modifications of the diagram, which have not yet been worked out, but which are of fundamental importance in those industries which utilise the high-speed cutting properties introduced by those elements. There is definite evidence of complex changes imperfectly understood taking place in the higher reaches of what is,

[1] W. H. Hatfield, "The Mechanical Properties of Steel, with some Consideration of the Question of Brittleness," *Inst. Mech. Engineers*, May 1919.

in the iron-carbide diagram, a solid solution phase. It will be clear that with such fundamental changes the micro-structures of the steels, after various treatments, are in no sense comparable with the structures obtained from carbon steels, but as each ternary or quaternary system would require a special section to itself, it is proposed to leave the subject here.

The binary systems are simple to investigate and have been fairly well done. The ternary systems are more complex and cannot be considered in any instance to have been investigated completely, whilst the quaternary and still more complicated alloys have not, as yet, been systematically attempted. Nevertheless, it will be found, on further perusal of this article, that some of the steels actually employed, notably the high-speed tool steels, contain as many as five special

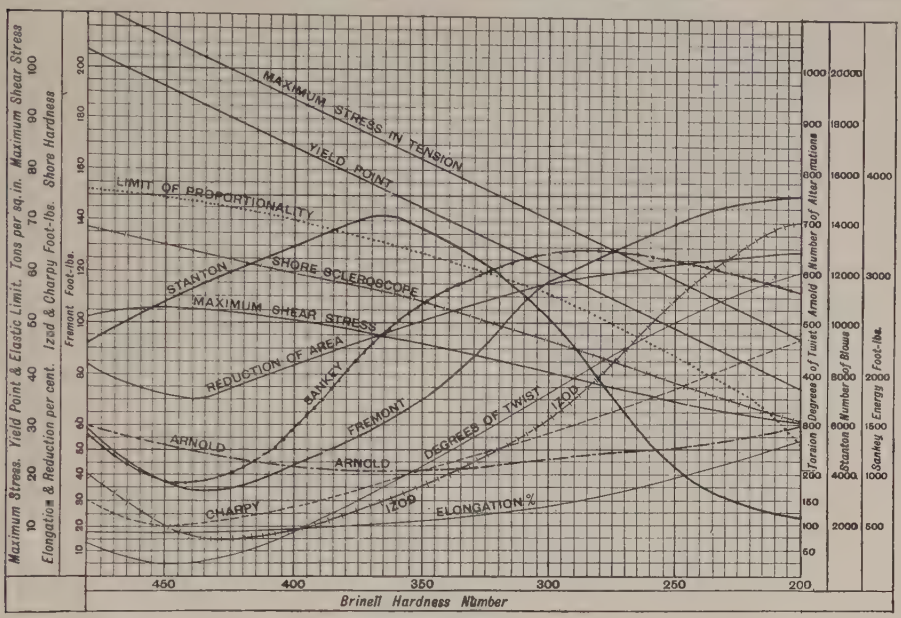
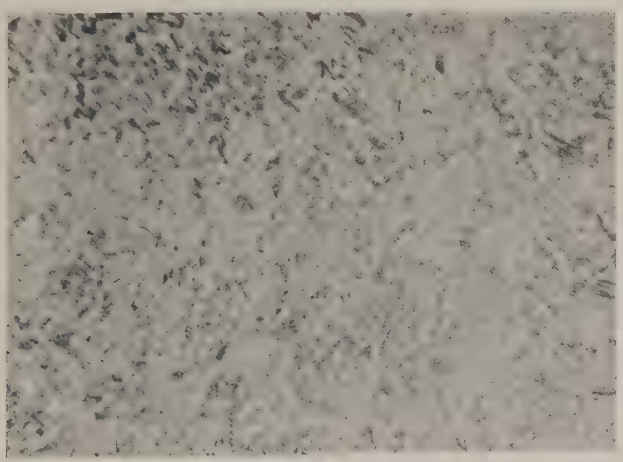
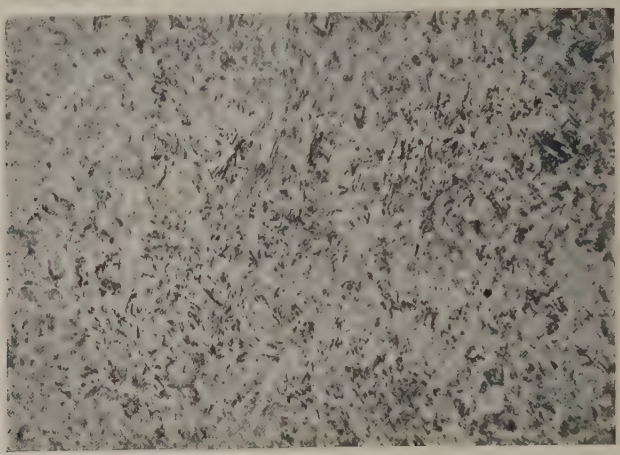


FIG. 1.—Nickel Chromium Steel. (Hardened and then tempered to gradually ascending temperatures.)

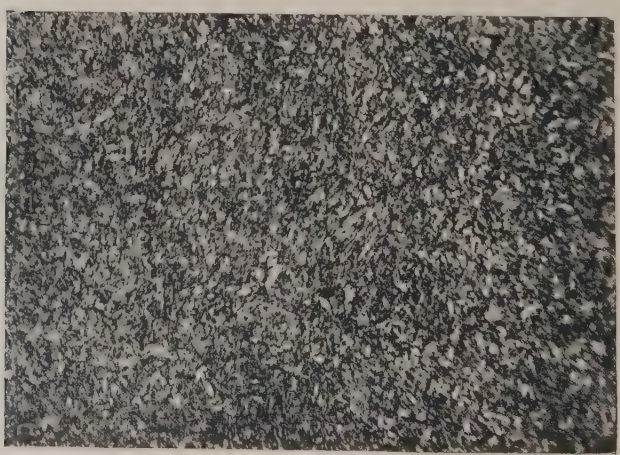


Micrograph A.—(Brinell 470.) Hardened 850° C. Tempered 250° C.



Micrograph B.—(Brinell 400.) Hardened 850° C. Tempered 400° C.

Micrograph C.—(Brinell 346.) Hardened 850° C. Tempered 500° C.



Micrograph D.—(Brinell 307.) Hardened 850° C. Tempered 600° C.

elements other than carbon and manganese. It will at once be obvious that such steels have not had their compositions determined by a conscious systematic research, but indicate to some considerable extent the survival of the empirical methods which had to be employed in the early stages of steel metallurgy. Many such alloys have, however, unique properties which have not as yet been obtained from more simple alloys.

Micrograph E.—(Brinell 248.) Hardened 850° C. Tempered 650° C.

§ (2) The Hardness of Special Steels.—In discussing the hardness of steel it is necessary that we should first of all fix upon a definite quantitative measure of that property. The methods employed in testing the hardness of steel are those devised by Brinell and Shore, full particulars of which will be found in the appendix to this article. It is of interest to endeavour to correlate the values obtained from the hardness tests with the general well-known scales of hardness applied, for instance, by the geologist and mineralogist. Moh's scale of hardness, for instance, consists of the varying hardnesses of the following series and order of minerals: (1) talc, (2) selenite, (3) calcite, (4) fluorspar, (5) apatite, (6) felspar, (7) quartz, (8) topaz, (9) corundum, (10) the diamond.

Investigations have been carried out, of a satisfactory quantitative type,[1] which clearly show that the whole range of steels, *i.e.* the softest steel to the hardest steel, lie, in terms

Micrograph F.—(Brinell 207.) Hardened 850° C. Tempered 700° C.

[1] R. A. Hadfield, *Inst. of Mech. Engrs.*, Jan. 1917, p. 762.

of Moh's scale, in the region covered by (4) fluorspar, (5) apatite, (6) felspar, and (7) quartz. It is considered that the hardest condition of steel corresponds, on Moh's scale, to a hardness of barely 7, whilst the softest condition corresponds to a hardness just under 4. The Brinell range covering these values runs from a Brinell number just over 100 to a Brinell number of 700. If we now desire to compare the hardness values obtained from the Brinell method with the Shore method, *Fig.* 2 is of interest, which summarises the results of numerous investigations made in the Brown-Firth Research Laboratories with a view to correlating the hardness by those two methods with the maximum stress, in tension, in tons per square inch.

The Brinell test, consisting as it does of the measurement of the impression made by a hardened steel ball, is obviously limited in its operation by the hardness of the ball. The steel used for making these Brinell balls is a high carbon steel with a small addition of chromium, and in the hardened condition is supposed to give the greatest hardness to be obtained from any type of hardened steel. If a high carbon steel, say 1·23-1·5 per cent carbon, is hardened in thin section, the hardness so obtained cannot be exceeded. This hardness is approximately 700 according to the Brinell scale and 95 to 100 according to the Shore values. Many of the special alloy steels which harden thoroughly in relatively large masses, *i.e.* harden more readily than carbon steels, do not possess in their hardest condition the same intrinsic hardness possessed by

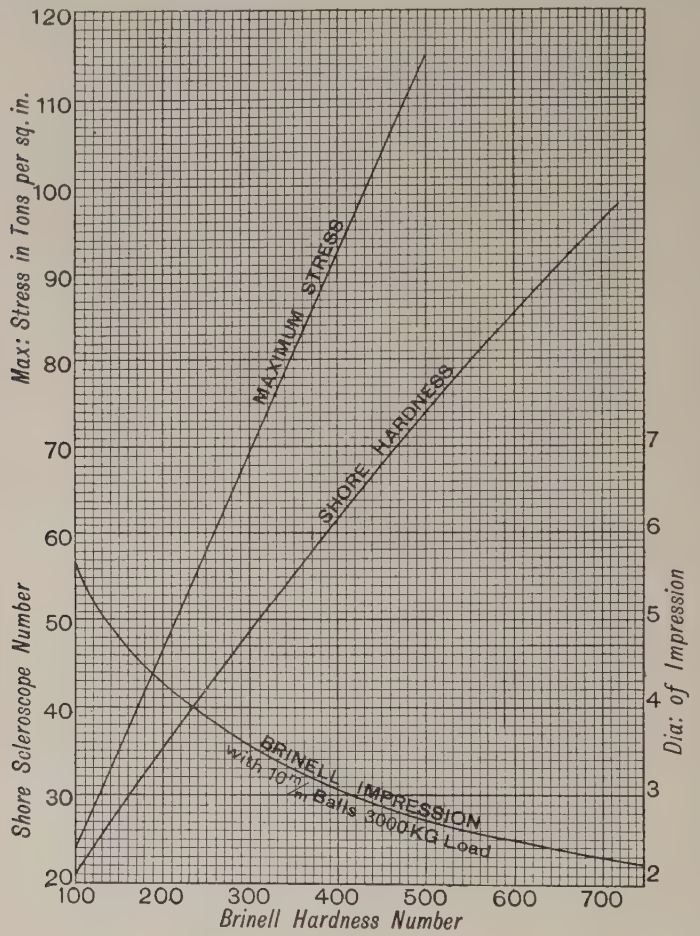


FIG. 2.

hardened high carbon steel. If properly hardened carbon steel or alloy steel is tempered to gradually ascending temperatures, the result is an ultimate and gradual softening, until Brinell values in the neighbourhood of and lower than 200 are reached. It is of interest to record that there are a number of alloy steels which, on tempering through the low range of temperature, say from normal temperatures to 300° or 400° C. and even higher, actually increase in hardness, owing to the tempering operation before the ultimate softening effect by still further increase of temperature is attained. However, to deal adequately with the whole of the different steels in this short article is impossible, and we shall have to leave the matter with these general observations. Wherever tables of mechanical properties, etc., are given it will be found that, when possible, the hardness values according to both the Brinell and Shore tests have been included.

Hardness should not be too readily accepted as a direct indication of properties which are usually associated with hardness, as there are several anomalies in the metallurgy of steel, such, for instance, as the case of the cutting properties of high-speed tool steels, the capacity for resisting wear and abrasion, etc. Whilst in both cases the hardness data are of interest and, indeed, essential, yet experiments show that this is not necessarily the determining factor.

Whilst dealing with the hardness of steels it is of interest to mention the change in hardness which takes place in various steels when they are maintained at gradually ascending temperatures. Changes in composition lead to some steels maintaining their hardness better than others at these high temperatures; see, for instance, Table 2, which gives the actual relative hardness of two steels at temperatures up to 700° C. from data derived from experiments conducted by the writer.

TABLE 2

EFFECT OF INCREASING TEMPERATURE ON HARDNESS IN BRINELL NUMBERS

° C.	Hardened Carbon Tool Steel.	Hardened High-speed Tool Steel.
15	680	652
100	680	652
200	680	620
300	530	570
400	385	530
500	300	490
600	180	483
700	125	365

§ (3) MECHANICAL PROPERTIES.—The mechanical properties of each of the typical steels now employed in the industrial arts will be found stated fully later in this article, and it is proposed, therefore, to deal only with the matter in general terms at this stage. In Appendix I. will be found a summary of the more useful and more generally used forms of test which are employed to measure the mechanical properties of steel.[1] The engineer is interested, in the first place, in the mechanical strength as measured by the maximum stress in tons per square inch, and, in the second place, with the ductility as measured by the elongation and reduction of area. The tensile and torsion test gives information of similar order. The data from the auxiliary tests such as the notched bar tests, alternate bending tests, etc., provide data which are considered to throw still further light upon the behaviour of such materials in service.

Speaking generally, the alloy steels may mostly be put into a whole range of conditions by hardening and tempering to various temperatures. Their tensile strength in tons per square inch will be found to range from figures approximating to 130 and 140 tons per square inch down to a tensile strength in tons per square inch in the neighbourhood of 40 tons. As the maximum stress falls the ductility increases (see *Fig.* 1). One interesting characteristic brought out by the notched bar tests is that small differences in heat treatment, particularly in the nickel-chromium steels, are liable to modify the ease with which a crack once started will propagate through a steel article made of such material.[2]

The Wöhler fatigue tests are becoming more appreciated and understood, since it is realised that the simple forms of test do not give information which always can be relied upon to give a true indication as to the value of the different materials under service conditions.

The Wear tests also, such as those devised by Stanton, Saniter, and others, are also coming to the front at the present time, since it is found that the ordinary forms of mechanical testing do not give reliable information as to the abrasion resistance of materials. In other words, as should be the case in a progressive science, the methods and the understanding of methods of mechanical testing are developing from year to year. Much work is required to be done on the resistance of steel to complex systems of stressing.

§ (4) THE INFLUENCE OF TEMPERATURE UPON THE PHYSICAL PROPERTIES OF IRON AND STEEL.—The structure and physical properties of steels at ordinary temperatures are considered under various headings throughout this article. The influence of high temperatures

[1] See also "Elastic Constants, Determination of," Vol. I.

[2] Philpott, *Institution of Automobile Engineers*, Stanton and Batson, *Inst. Civil Eng.*, Dec. 1920.

is already a question of the greatest industrial importance; and whilst the influence of very low temperatures is as yet mainly of scientific interest, there are signs that the industrial interest has become real. The data extant for the consideration of these aspects of steel metallurgy, whilst relatively scanty, are quite important.

(A) The Influence of Low Temperatures.—It may appear only of scientific interest to study the effects of temperatures so low that they are well on the way to absolute zero, but if such interesting and, by the way, costly experiments provide us with distinctly unexpected modifications in properties we are much to the good, if for no other reason than that a study of the metal in such a condition will probably enable us to accomplish similar modifications of properties at high temperatures. The following interesting quotation from Sir R. A. Hadfield's 1914 Faraday Society address will illustrate this aspect.

"Recent experiments in America show that at a temperature of about minus 435° F., or close upon absolute zero, metals lose their resistance to such a remarkable degree that the energy developed at the power-house of Niagara, so it is stated, could be transmitted over a quite small metallic wire, simply because resistance vanishes at these temperatures. It will therefore be seen that there is good ground for my statement that before long we may have to consider not merely heat treatment effects, that is an increase over normal temperature, but also treatments below normal temperature."

Probably one of the earliest investigators in this field was Mr. T. Andrews, F.R.S. (Sheffield), who read a paper before the Civil Engineers in 1886 dealing with the influence of cold upon railway axles. The subject was obviously a live one, and Mr. Andrews carried out distinctly practical experiments down to temperatures as low as −45° C., showing that resistance to shock decreased. Sir James Dewar and Dr. Fleming published a series of researches, commencing in 1892, dealing with the electrical and magnetic properties of metals which were of great assistance in forming modern views concerning those properties, and incidentally pointed out that different metals were affected in diverse ways. Sir James Dewar definitely indicated that the strength became much greater with decreasing temperature, and that Young's Modulus of Elasticity was found to be greatly increased.

To Professor Rudeloff we are indebted for interesting work upon wrought iron and mild steel, which indicated a stiffening of these materials with lower temperatures.

In 1905,[1] however, Sir R. A. Hadfield published his researches dealing with iron and its alloys, and in his paper will not only be found a detailed account of his own work, but also an excellent bibliography. It may be mentioned that both Sir James Dewar and Professor Barrett assisted with the work. To subdivide the data will probably simplify the study of the comparative results. The paper under discussion contains a mass of data which should be carefully studied, and the writer therefore only proposes to select such figures as will indicate the trend of the deductions. The discussion which followed the reading of the paper, and in which most of our leading metallurgists took part, should also be considered.

[1] *J.I. and S.I.*, 1905, i. 147.

(i.) *Wrought Iron.*—Wrought iron is the nearest approximation to the pure metal used in the research, and may therefore conveniently be studied as the starting-point. The results here given average the figures obtained from six different irons which analysed: carbon, 0·04 per cent; silicon, 0·07 per cent; sulphur, 0·005 per cent; phosphorus, 0·004 per cent. At normal temperatures the maximum stress in tons per square inch was 20 to 25, accompanied by elongations of 20 to 30 per cent. A lowering of the temperatures resulted in a stiffening of the material, tensile strengths of 40 to 54 tons per square inch being obtained at the temperature of liquid air, *i.e.* −182° C., but at the same time, it may be pointed out, the elongation was reduced to nil. The hardness registered by the Brinell test showed that a figure of 90 for normal temperatures became 260 for the temperature of liquid air.

Interesting figures were produced relating to the specific resistance, which may be indicated as follows:

	Microhms per Cubic Centimetre.
Temperature of boiling water, 100° C.	15·0
Normal temperature 18° C. . .	11·0
Temperature of liquid air −182° C. .	2·0

Dr. Fleming found that the permeability was only very slightly increased at the temperatures so low as −185° C.

(ii.) *Other Pure Metals.*—As an instance of the influence of cold upon other simple metals, nickel, copper, and aluminium may be selected:

	Nickel.	Copper.	Aluminium.
Normal temperatures—			
Max. stress, tons/sq. in.	29·0	15	8
Elongation, per cent .	43·0	42	7
−182° C.—			
Max. stress, tons/sq. in.	46·0	23	15
Elongation, per cent .	51·0	45	27

The figures require very little comment. Suffice it to point out that whereas iron became

brittle, the ductility of nickel becomes considerably greater.

(iii.) *Carbon Steels.*—Turning now to steels: we have seen the comparative influence of cold upon pure metals, and so the first question to answer is, What is the influence of the carbon? The following figures will prove illuminating:

Carbon.	0·14 per cent.	0·24 per cent.	0·37 per cent.	0·50 per cent.	0·78 per cent.	0·83 per cent.	1·09 per cent.	1·20 per cent.
Normal temperature, 18° C.—								
Maximum stress, tons/sq. in.	23·0	41·0	34·0	48·0	45·0	51·0	56·0	59·0
Elongation, per cent	36·0	22·0	20·0	15·0	5·0	12·0	5	10
Hardness (Brinell)	..	..	165	..	..	..	..	..
−182° C.—								
Maximum stress, tons/sq. in.	61·0	64·0	66·0	66·0	69·0	70·0	76·0	74
Elongation, per cent	7·5	7·5	17·0	2·5	Nil	Nil	Nil	Nil
Hardness (Brinell)	..	..	338	..	..	..	..	..

It will be noticed that the considerable increase in tensile strength induced by the increase of carbon at normal temperatures is only reflected in small degree at −182° C.

(iv.) *Nickel Steels.*—We have seen that the ductility of nickel is increased with low temperatures, and it will be seen that the addition of this element to steels assists in the preservation of this property at low temperatures.

Steels containing 0·14 to 0·19 per cent Carbon

Nickel.	1·92 per cent.	3·82 per cent.	11·39 per cent.	19·64 per cent.	24·51 per cent.
Normal temperature—					
Maximum stress, tons/sq. in.	34·0	36·0	90·0	100·0	90·0
Elongation, per cent	20·0	20·0	5·0	2·5	12·0
−182° C.—					
Maximum stress, tons/sq. in.	59·0	57·0	115·0	118·0	118·0
Elongations, per cent	12·0	17·0	5·0	2·5	10·0

Steels containing 0·70 to 0·93 per cent Carbon

Nickel.	0·76 per cent.	12·08 per cent.	31·4 per cent.
Normal temperatures—			
Max. stress, tons/sq. in.	66·0	88·0	41·0
Elongation, per cent	10·0	Nil	30·0
−182° C.—			
Max. stress, tons/sq. in.	79·0	80·0	111·0
Elongation, per cent	2·5	Nil	10·0

(v.) *Manganese Steels.*[1]—The data given in table on following page will indicate the influence of manganese.

It was found that with high carbon steels the tenacity was not materially increased, but that the elongation was reduced to nil. It is interesting to note that Hadfield's manganese steel persisted in the non-magnetic condition down to −182° C., which of course indicates that the temperatures of the breaking down of the solid solution had not been reached even by so low a temperature.

(vi.) *Other Steels.*—Amongst other numerous experiments recorded it may be noted that chromium steels had their tenacity moderately increased and their elongations reduced to nil by a temperature of −182° C. The same thing appears to happen to tungsten steels, whilst copper steels are interesting in so far as the tensile is greatly increased, the elongation reduces to a very low figure. As an instance of the influence of cold upon a typical alloy steel, it is interesting to note that a nickel chrome steel (carbon, 0·44 per cent; chromium, −1·71 per cent; nickel, 3·5 per cent) had its maximum stress increased from 69 tons to 97 tons per square inch, whilst its elongation remained stationary at 12 per cent.

This research brings into the field data that will ultimately prove of much value.

(B) The Influence of High Temperature.—The influence of temperatures above the normal upon the several physical properties of different steels is dealt with under different headings where such data are available. To consider specially the strength of steels as affected by increasing temperature, comparatively little experimental work has been published, but several researches will repay

[1] See article "Manganese Steel."

Steels containing 0·08 to 0·15 per cent Carbon

Manganese.	Air-cooled.		Quenched 1048° C.	
	3·5 per cent.	5·4 per cent.	10·08 per cent.	15·27 per cent.
Normal temperatures—				
Maximum stress, tons/sq. in. . .	66·0	66·0	56·0	39·0
Elongation, per cent . . .	7·5	Nil	1	5
– 182° C.—				
Maximum stress, tons/sq. in. . .	88·0	61·0	52·0	46·0
Elongation, per cent . . .	Nil	Nil	Nil	2·5

study.[1] This subject is extremely important, as evidenced by the large development of the internal combustion engine, and several important researches are at present in progress both in this country and abroad. If wrought iron is heated, it hardens up and loses some of its ductility, but with subsequent increase in temperature it rapidly softens and increases its capacity for plastic deformation (see Table 3). Mild carbon steel is affected similarly. The influence of the addition of the special elements is found to materially affect the degree of softening attained for a given temperature, and this is particularly instanced in the case of high chromium steels and steels containing much tungsten stainless high chromium steel respectively, based on work by Aitchison.[2]

From the hot-working point of view, *i.e.* forging, pressing, or rolling, it is of interest to record that at forging temperatures 1050° C. to 1200° C., alloy steels generally, like carbon steels, have tensile strength of about 1 to 1·5 tons per square inch, accompanied by a reduction of area of 90 to 99 per cent. It will, however, be appreciated that the alloys added to the steel generally increase its strength with increasing temperature, so is the lowest temperature at which it may be economically and satisfactorily forged increased.

(ii.) *Hopkinson's Investigations.*—When considering the properties of steel when exposed

Table 3

Temperature. ° C.	Wrought Iron.			Mild Carbon Steel.			Annealed Nickel Chromium Steel.		
	Maximum Stress.	Elongation per cent.	Reduction of Area per cent.	Maximum Stress.	Elongation per cent.	Reduction of Area per cent.	Maximum Stress.	Elongation per cent.	Reduction of Area per cent.
15	24·34	29·0	48·43	27·2	38·0	61·0	37·0	34·0	66·0
200	..	..	..	30·0	27·0	58·0	32·5	29·6	68·5
300	30·25	20·0	31·4	32·5	23·2	55·8	34·0	27·2	65·0
400	..	..	..	25·2	37·6	68·5	34·8	33·6	65·8
500	15·0	36·8	51·4	20·0	38·0	73·0	23·5	39·5	82·0
600	..	..	..	12·5	48·0	86·0	13·5	47·0	93·5
700	4·78	32·0	52·7	6·8	56·0	93·0	8·3	56·0	96·5
800	..	..	..	4·0	65·0	96·0	5·2	66·0	97·0
900	..	..	..	2·0	75·0	98·0	3·0	76·0	98·0

(i.) *Temperature and Tensile Strength.*—In Table 3 will be found the effect of temperature upon the tensile properties of wrought iron, low carbon steel, and a nickel chromium steel as determined in the Brown-Firth Research Laboratories. In Tables 4 and 5 will be found the effect on two high-speed steels and upon to high temperatures a reference to the valuable work of Hopkinson and Rodgers[3] must not be omitted. These workers investigated the elastic properties of steel and iron at temperatures ranging up to 800° C. at stresses considerably below those required to rupture the material. They found that as the temperature rose the stress strain relations became considerably modified, and a simple change, which may be best described as "time effect" or "creeping," increased greatly with the temperature. They point out that steel at high temperatures actually behaves like india-

[1] Guillet and Revillon, *Proc. Internat. Assoc. Test Materials*, 1909, iii.; Rosenhain and Humfrey, *Proc. Royal Soc.*, 1909, lxxxiii. 200; Bengough, *J. Inst. Metals*, 1912, No. 2, viii. 176-177; A. K. Huntington, *J. Inst. Metals*, 1912, viii. 126-144; Honda and Takagi, *Math. Phys. Soc. Tokyo Proc.*, 1912, (6) xx. 294-306; Rosenhain and Ewen, *J. Inst. Metals*, 1912, No. 2, viii.; Rosenhain and Humfrey, *J. Iron and Steel Inst.*, 1913, i.; Bregowsky and Spring, *Rev. de Métallurgie*, 1913, x. 111-123; A. K. Huntington, *J. Inst. Metals*, 1914, No. 2, xxi.; Epps and Jones, *Met. and Chem. Eng.*, 1917, xvii. 67-71.

[2] *Institution of Automobile Engineers*, 1919.

[3] *Proceedings of the Royal Society*, Series A, lxxvi. 419-425.

rubber or glass, *i.e.* if it be stressed for a time and then the stress be removed it does not at once recover its original size, but after the immediate elastic recovery there is a further slow contraction perceptible for many minutes. They observe that such creeping cannot be

TABLE 4

TUNGSTEN STEELS

Composition	Carbon	0·71	0·43
	Tungsten	17·30	12·10
	Chromium	3·86	3·19
	Vanadium	0·75	..
M.S, tons/sq in at	15° C.	58·4	50·0
	650	24·7	20·1
	750	13·2	10·0
	800	10·3	7·1
	860	11·1	9·6
	900	8·8	8·2
	950	6·6	..

detected at ordinary temperatures, but that at a red heat it attained a different order of magnitude, becoming in its total amount a substantial fraction of the whole deformation. They consider that this phenomena is analogous to residual charge in glass or other di-electrics; the stress corresponding with the electric force and the strain to the electric displacement. The magnitude of this creeping in steel may best be measured by a comparison

TABLE 5

STAINLESS STEEL (12 TO 14 PER CENT CR)

Temperature of Specimen. ° C.	Yield Point. Tons/sq. in.	Maximum Stress. Tons/sq. in.	Elongation per cent.	Reduction of Area per cent.
18	38·8	48·5	27·5	59·3
100	37·0	43·5	21·0	54·6
200	37·0	44·0	21·0	55·8
300	33·4	39·6	18·5	57·0
400	33·6	39·9	17·5	53·6
450	31·3	34·9	18·5	63·7
500	28·7	29·7	22·0	71·7
600	20·8	24·2	25·0	75·9
700	10·8	12·1	40·0	90·9
800	5·1	6·6	40·5	91·9
850	4·7	6·6	40·5	92·4
900	3·8	4·8	41·0	65·8
970	2·0	4·0	31·5	52·2

with other cases of a similar kind, and they instance the slow recovery of a glass fibre after twisting; if such a fibre be twisted to a considerable angle for a definite period it will recover within two or three seconds of the removal of the stress all but one-fiftieth of the twist. The remaining recovery, amounting to about one-fiftieth of the whole deformation, corresponds to the slow return of the steel. In india-rubber, under certain circumstances, 10 per cent of the strain disappears in time after removal of the stress, but in steel at 600° C. the proportion is as high as 15 per cent. They state that another effect of creeping is to make the determination of Young's modulus a matter of some uncertainty. Thus the extension of the bar at 600° C. produced by a given load varies 15 per cent or more according to the time of application of the load. They point out, however, that when the load is applied for only a very short time, say one or two seconds, the strain produced seems to approach a definite limiting value, which is the instantaneous extension or contraction of the bar observed in the experiments when the load is applied or removed. They consider that one might define the Young's modulus for a metal in this state, as the stress divided by this limiting instantaneous strain. It is independent of the manner of loading and quite a definite physical constant. This creeping of steel at high temperatures is of great practical interest, and must be familiar to our practical steel workers. From the theoretical standpoint two papers, contributed by Rosenhain and Humfrey,[1] are particularly interesting, since apart from the general effect of increase of temperature they sought to determine changes in strength coincident with changes in phase. They conclude that the softening effect up to the Ac_3 change is there reversed, and that with the appearance of the Gamma phase a slight temporary hardening is observed. The writer would, however, suggest that the tables of data already furnished give for engineering purposes a reliable indication of the changes in strength taking place with increasing temperature.

§ (5) SPECIFIC GRAVITIES. — The specific gravities of various steels are materially affected by composition. The specific gravity of pure iron may be taken as 7·892. If we go from pure iron to the carbon steels we find that the specific gravity slightly decreases as the carbon rises; for instance, carbon tool steel with a carbon content of 1·20 per cent will have a specific gravity of 7·86. Chromium also tends to decrease the specific gravity, and the writer has found that a 14 per cent chromium steel has a specific gravity of approximately 7·76 when in the annealed condition. On the other hand, nickel and manganese are responsible for slight increases. Thus, 25 per cent nickel steel has a specific gravity of 7·96, whilst 14 per cent manganese steel has a value of 7·87. The influence of high silicon is in the direction of reducing the specific gravity, and this is emphasised by the acid resisting 15 per

[1] *Royal Society Proc.* A, lxxxiii.; *Jour. Iron and Steel Inst.*, 1913, i. p. 219.

cent silicon alloy with iron which has a specific gravity of only 6·83. To take high-speed tool steels: tungsten causes a substantial increase, and this may be judged from the fact that a 14 per cent tungsten steel has a specific gravity of 8·57, whilst an 18 per cent tungsten steel is in the neighbourhood of 8·70. Cobalt and molybdenum have similar effects. In the ordinary way the sulphur, phosphorus, and silicon present in steel are not there in sufficient quantity to have any measurable effect. The preceding figures are quoted as regards the soft condition of the steel. In nearly all cases the hardened condition has a slightly lower specific gravity, the extent depending on the composition of the steel. The greatest reduction, owing to the preservation of the hard condition, however, is only about 0·05 in the specific gravity. One interesting exception is the 12-14 per cent manganese steel, which is hardened by tempering, and, when hardened, has actually a greater density in the harder condition than in the Gamma condition, which, however, does not correspond to the soft condition of ordinary steels.

The data given in Table 6, prepared as a result of experimental work in the Brown-Firth Research Laboratories, may be of interest.

TABLE 6

Material.	Treatment.	Brinell Hardness.	Specific Gravity.	Lbs. per Cubic Foot.
Dead mild steel, 0·08 per cent carbon	Normalised	92	7·892	492·0
	Water-quenched, 760° C.	190	7·865	490·1
Medium carbon steel forging	Normalised	159	7·854	489·4
Tyre steel	Normalised	234	7·837	488·4
Carbon tool steel	Normalised	198	7·859	489·9
	Water-hardened, 780° C.	575	7·816	487·1
Nickel-chromium steel	Hardened and tempered	237	7·858	489·7
Air-hardening nickel-chromium steel	Air-hardened	477	7·821	487·4
Stainless steel	Knife temper	500	7·751	483·0
Manganese steel	Water-quenched, 900° C.	250	7·875	491
25 per cent nickel steel	Water-quenched, 900° C.	191	7·936	494·7
Tungsten magnet steel	As rolled	320	8·159	508·5
Tungsten high-speed steel	Hardened	600	8·514	530·7
	Annealed	321	8·610	536·6

§ (6) EXPANSION OF STEELS.—The influence of the various elements on the dilatation of steels has received comparatively little attention from investigators, but there are, fortunately, several works dealing with the influence of some of the elements to which reference should be made.[1] The best determinations of the coefficient of expansion of pure iron give ·0000116 for the temperature range 20° to 100° C. Between 20° and 500° C. the mean coefficient is ·0000142, and between 20° and 900° C., ·0000131. The influence of the various elements on the dilatability is very small except in some cases of steels near the critical compositions. For ranges of temperatures between 20° and 200° C. there is a lowering of the dilatability with increase of carbon content, for ranges between 200° C. and 600° C. the expansion for all percentages of carbon is practically the same, whilst for higher temperatures still there is a gradual increase in the dilatability. Tungsten causes a slight lowering of the coefficient of expansion for all ranges of temperature. For ranges of temperature up to 100° C. manganese first causes a small drop in the expansion until ·9 per cent manganese is reached; there is then a maximum about 3 per cent manganese, after which there is a gradual drop till a percentage of 7 per cent is reached, when there is a sharp rise coincident with the appearance of iron in the austenitic condition. A similar state of affairs exists for temperature ranges about 500° C., but at 800° C., after the first small drop, there is a gradual rise of dilatability with increasing content of manganese. Nickel causes a slight rise in the coefficient of ex-

[1] CARBON STEELS.—K. Honda, *Tôhoku Imp. Univ. Sci. Reps.*, Nov. 1917, No. 4, vi. 203; Driesen, *Ferrum*, Feb. 8, 1914, ix. 129; Dittenberger, *Mitteilungen, Forschungsarbeiten auf dem Gebiete des Ingenieurwesens*, xcix. 60; Dulong and Petit, *Annales chim.-phys.*, 1817, vii. 113; Andrews, *Poggendorfs Annal.*, 1869, cxxxviii. 26, and *Proc. Roy. Soc.*, 1887–88, xliii. 299; Svedelius, *Phil. Mag.*, 1898, xcvi.; Le Chatelier, *Comptes Rendus*, 1893, cxxix.

MANGANESE STEELS.—T. Matsushita, *Tôhoku Imp. Univ. Sci. Reps.*, August 1919, No. 2, viii. 79.

TUNGSTEN STEELS.—K. Honda and T. Matsushita, *Tôhoku Imp. Univ. Sci. Reps.*, 1919, No. 2, viii. 89.

CHROMIUM STEELS.—T. Matsushita, *Tôhoku Imp. Univ. Sci. Reps.*, June 1920, No. 3, ix. 243.

NICKEL STEELS.—G. E. Guillaume, *Comptes Rendus*, 1897, cxxiv. 176; *Bureau of Standards Circular*, April 1916, No. 58; Charpy and Grenet, *Bulletin de la Société d'Encouragement pour l'Industrie nationale*, 1903, p. 464.

"Expansion at High Temperatures," Andrew, Rippon, Miller, and Wragg, *Jour. Iron and Steel Inst.*, May 1920.

pansion up to 20 per cent, when there is a sharp rise reaching a maximum at 25 per cent, and then a very low minimum at 36 per cent nickel (invar) at normal temperatures. For ranges of temperature between 400° and 600° C. and 600° and 900° C. the changes in the dilatability are similar, but the maximum and minimum occur at slightly lower percentages of nickel. Chromium causes first a slight increase in the coefficient of expansion, between 0° and 100° C., reaching a maximum at 3 per cent of chromium, after which there is a gradual fall until 10 per cent is reached, a further addition of chromium causing no change in the dilatability. For a range of temperature between 0° and 500° C. the coefficient falls gradually with increase of chromium content.

§ (7) Specific Heats.—The specific heat of pure iron has been determined by J. A. Harker.[1] He gives ·1175 for the value of this constant between 0° and 200° C., ·1282 between 0° and 400° C., ·1597 between 0° and 800° C., and ·1534 between 0° and 1100° C. Little work has been done to determine the influence of various elements on the specific heat of steels. Ingersoll [2] measured the change in specific heat with varying percentages of nickel. W. Brown [3] determined the influence of various elements in steels which had been water-quenched from a bright red heat (about 900° C.). He gives the following summary of his results, the specific heats being measured for a range of temperature between 0° and 100° C. Each 1 per cent of added carbon increases the specific heat by ·0089. Each 1 per cent of manganese increases the specific heat by ·0006. Between 0 and 4 per cent, 1 per cent of nickel increases the specific heat by ·0038, between 4 per cent and 20 per cent it has no effect, whilst from 20 per cent to 30 per cent of nickel, 1 per cent decreases the specific heat by ·0050. The first 1 per cent of tungsten increases the specific heat by ·0028. Further tungsten causes a gradual drop in the specific heat, so that at 3·5 per cent of tungsten it is the same as that for pure iron; a further increase of 12 per cent of tungsten decreases the specific heat by ·0093. Up to 2 per cent of silicon each 1 per cent causes an increase of ·003 in the specific heat. Over this amount silicon has no effect. Aluminium, chromium, copper, and cobalt have little effect on the specific heat, especially when large amounts of carbon are present.

§ (8) Permeability.—If one examines technical literature little experimental data are to be found covering this physical property of steel beyond the notable contribution given by Hadfield and Hopkinson.[4] The permeability, particularly of large forgings, is now a matter of immediate interest, and no doubt experimental work will be forthcoming. Some facts are, however, well established.[5] For instance, it is known that an increase in the carbon content results in a definite reduction in the permeability of steel. It is also known that elements such as nickel increase the permeability.

Elsewhere [6] will be found data concerning the fact that silicon has the interesting influence of substantially decreasing the hysteresis losses.

§ (9) Magnetic Properties.—A survey of metallurgical literature discloses very few really useful researches in this field. In the first place, permanent magnets were produced from high carbon tool steels and it was found that in the properly hardened condition reasonable values could be obtained, such, for instance, as a coercive force of 45 with a remanence of 9000. A substantial improvement on carbon steels was brought about with the introduction of tungsten steels, which usually have between 3 and 6 per cent of tungsten. Properly treated tungsten steels will give, with a coercive force of 55-65, a remanence of 9-11,000. Some experimental work has been done both at home and abroad on chromium magnet steels, and it has been found that similar results to the tungsten steels may be obtained from chromium steels. There are, however, now on the market several more complicated steels which give still higher values, as, for instance, a coercive force of 75 with a remanence of 10-12,000. Molybdenum, cobalt, vanadium, and a number of elements have been experimented with, but there is little quantitative evidence available for presentation in this work.[7]

A substantial development as regards magnet alloys has recently taken place as a result of experimental work by Professor Honda, which led to the discovery of the fact that rich cobalt alloys might be prepared with a coercive force of 200-240 with a remanence of about the usual value for ordinary magnet steels. There is little published work dealing with these alloys, but the writer looks

[1] National Physical Laboratory, *Collected Researches*, xi. 207, and *Proc. London Phys. Soc.* xix.
[2] *Amer. Phys. Rev.*, Aug. 1920, p. 126.
[3] *Trans. Roy. Dub. Soc.*, 1905–9, Series 2, ix. 59.
[4] Hadfield and Hopkinson, *Inst. Elect. Engrs.*, 1911, xlvi.
[5] Barratt, Brown, and Hadfield, *Trans. Roy. Dub. Soc.*, 1900; *Proc. Inst. Elect. Engrs.*, 1902; Honda, *Tôhoku Imp. Univ. Sci. Reps.*, 1919, No. 1; Matsushita, *Tôhoku Imp. Univ. Sci. Reps.*, 1919, No. 2.
[6] Guhmlich, *Annalen der Physik*, 1911, p. 235.
[7] Barratt, Brown, and Hadfield, *Trans. Roy. Dub. Soc.*, 1900, and *Proc. Inst. Elect. Engrs.*, 1902; T. Yensen, *Illinois Univ. Eng. Exp. Station*, 1915, Bulletin 83; Yensen and Gatward, *Illinois Univ. Eng. Exp. Station*, 1917, Bulletin 95; Swinden, *Inst. Elect. Engrs.*, 1909, xlii.; Curie, "Prop. mag. des aciers trempés," *Bull. de la Soc. d'Encouragement*, 1898, iii.; Weiss, *Inst. Assoc. Test. Materials*, 1910; Honda; G. Mars, *Stahl und Eisen*, Oct. 27, 1909; Brown, *Proc. Roy. Dub. Soc.* xii. 318; General Discussion, *Trans. Faraday Soc.*, Sept. 1912, viii.

with interest to a definite development in this field of metallurgy.

§ (10) Thermal Conductivity.—Although this is a most important property, particularly in connection with metallurgical operations, not much information has been obtained since the work of the earlier physicists—Forbes, Tait, Stewart, Ångström, and Gray—until quite recent years. Most of the determinations by the above experimenters were on non-ferrous materials. Prof. C. H. Lees, F.R.S.,[1] and Mr. A. Johnstone, B.Sc.,[2] have also investigated several problems in this connection.[3]

Generally speaking, for all metals and alloys thermal conductivity varies in the same direction and runs parallel to electrical conductivity. This is in accordance with Wiedemann-Franz's law.[4] According to J. J. Thomson's electron theory the ratio of thermal to electrical conductivity should be constant from metal to metal, and proportional to absolute temperature. There are, however, rather wide variations from this law.

The thermal conductivity of metals does not vary much with temperatures above the normal. High carbon steels are less conductive than low carbon steels, and alloy steels generally still less, while the same steels when hardened offer further obstruction to the passage of heat. The influence of composition is not yet well known, and reference should be made to the papers by Campbell and Dowd,[5] Simidu,[6] Honda and Matsushita,[7] and L. R. Ingersoll,[8] for more detail.

§ (11) Electrical Conductivity.—Of the various physical properties of different types and conditions of steel, electrical conductivity (or its reciprocal electrical resistivity) has perhaps received most attention. This is not so much due to the utility of the results in practice, but rather to the help which such data appear to give in studying and interpreting the changes that take place in steel when the composition and heat treatment of the steel are each varied. The principal earlier workers in this field were Mathiessen[9] (about 1860), Barus and Strouhal,[10] Hopkinson,[11] Le Chatelier,[12] Barratt, Brown, and Hadfield,[13] and Benedicks.[14] A most useful simple formula laid down by Benedicks was as follows:

$$R = 7{\cdot}6 + 26{\cdot}8\,\xi C \text{ microhms per cm. cube,}$$

where R is the specific resistance of the sample of steel in question and ξC is the result obtained by adding together the percentages of other elements present in solution, each expressed as "carbon equivalents." Iron carbide out of solution (as in annealed steels) was considered to have a negligible effect. Much data has been accumulated since that time, and modified relationships have been worked out,[15] but it can hardly be said that these give really satisfactory agreement with actual measurement except over narrow ranges of composition. It may be taken approximately, however, that pure iron has a specific resistance of 9·8, that 1 per cent carbon in solution increases this to 44, and that each 1 per cent of the following elements adds to the resistance by the amount stated: manganese 5·5, silicon 13·5, aluminium 12·0, nickel 1·5. The effect of other elements is less definite. A useful *résumé* of this subject will be found in the *Journal of the Iron and Steel Institute*, 1920, by A. L. Norbury, M.Sc., which also contains a short bibliography.

II. A Consideration of the Binary, Ternary, Quaternary, etc., Alloys

From previous remarks it will be clear that the experimental evidence does not exist at present sufficiently to permit of a complete treatment of this aspect of alloy steels. It was thought, therefore, that the matter might best be dealt with by summarising the influence of the elements individually upon the iron-carbon system, and this has been done in some detail. Generally speaking, the influence of the fourth element, as in the creation of the several complicated quaternary systems, may be to some extent usefully predicted as result of pilot alloys. The quaternary system upon which the most work has been done is that of iron-carbon-nickel-chromium, but even there data at present available are insufficient for a proper consideration of the subject. It is proposed, therefore, to leave this aspect of the matter until the several steels actually in industrial use are discussed.

Many elements have been added or suggested as useful additions to steel for the purpose of modifying its properties in some desired direction. The proof of their usefulness is indicated effectively by the extent to which commercial use is made of their influence. In the following statements the elements are

[1] *Phil. Trans. Roy. Soc.*, 1908, and *Proc. London Phys. Soc.*, 1917.
[2] *Proc. London Phys. Soc.*, 1917.
[3] See also E. H. Hall, "Thermal Conductivity of Iron," *Phys. Rev.*, May 1900.
[4] *Pogg. Ann.*, 1853.
[5] *J.I. and S.I.*, 1917, ii. 251.
[6] *Tôhoku Univ. Sci. Reps.*, 1917, vi. 3.
[7] *Ibid.*, 1919, viii. 1, viii. 2, and viii. 12, and 1920, ix. 3.
[8] *Amer. Phys. Review*, Aug. 1920.
[9] Mathiessen, *British Assoc. Reports*, 1862, 1863.
[10] Barus and Strouhal, *Bulletin U.S. Geological Survey*, 1885, ii. No. 14.
[11] Hopkinson, *Phil. Trans.*, 1885, i. 176.
[12] Le Chatelier, *Comptes Rendus*, 1898, cxxvi. 1709-1782.
[13] Barratt, Brown, and Hadfield, *Jour. Inst. Elec. Engrs.*, 1902, xxxi. 729.
[14] Benedicks, *Recherches phys. et phys.-chimiques sur l'acier au carbone*, Upsala, 1904.
[15] Simidu, *Univ. Tôhoku Sci. Reps.*, 1917, vi. No. 3.

arranged in the order of the groups to which they belong:

§ (12) Hydrogen (Group 1, atomic weight 1·01, melting-point −259° C.).—This element is present in all steels, but only in extremely small quantities. It does, however, occur in several manufacturing processes in connection with steel metallurgy, and is therefore worth carefully considering.

Heyn [1] discusses the presence of hydrogen in steel, and mentions Sir William Roberts-Austen's experiments with electro-deposited iron, and points out that this metal, having the hardness of fluorspar, evolved large quantities of hydrogen at 70° C. Further quantities were given off with higher temperatures, and the evolution did not cease even at 1300° C. Heyn then proceeds to describe experiments performed at Charlottenburg with different iron and steel in which such materials were heated in atmospheres of hydrogen. Very little hydrogen was taken up by the samples. The brittleness and hardness of electrolytic iron as deposited seems unquestionably to be due to the presence of hydrogen, and this hydrogen can be sufficiently removed by heating the sample to 1000° C., after which it has lost its brittleness. It is claimed that the "pickling" process results in hydrogen being taken up by the metal in proximity to the acid, but experimental evidence in support of that fact is not complete.

The solubility in molten iron has been studied by Sieverts,[2] along with the comparative solubility of the gas in copper and nickel. On cooling down all three metals give off the gas somewhat violently during freezing, and it is stated that the relative amounts of hydrogen given off by the three metals were, in the experiments, iron 7 volumes, nickel 12 volumes, copper 2 volumes. The hydrogen taken up by liquid steel is, in practice, kept in solution in the steel by the silicon, manganese, and sometimes by the addition of aluminium. The amount of hydrogen so present in steel may be taken to be between the limits of 0·002–0·36 of a cubic centimetre of hydrogen per gramme of metal.

Charpy and Bonnerot [3] have shown that hydrogen will diffuse through iron and steel at temperatures above 350° C., the diffusion being greatly encouraged by an increase of temperature. They also suggest that, during such passages of the hydrogen through the steel, sulphur, phosphorus, and carbon may form hydrides and be removed.

§ (13) Copper (Group 1, Family B, atomic weight 63·6, melting-point 1083° C.).—Copper is found in some of the crude pig irons and, therefore, finds its way, to some extent, into a considerable tonnage of commercial steel. It was long held to have a detrimental influence upon the properties, such, for instance, as making the steel "red-short." Much work of late years, however, has been done upon the influence of the element, and it has now been definitely established that the influence is not detrimental. Indeed, the contrary is the case. Industrially, copper as an added element to steel is of interest from two points of view. In the first place, it has been shown definitely by American investigators that the addition of small quantities, *i.e.* in the neighbourhood of up to 0·2 per cent, markedly increases the resistance of low-carbon steels to corrosion,[4] although if much higher percentages are present the influence ceases, and indeed is suggested to be in the opposite direction. However, small percentages of copper are added for this purpose. When considering the alloy steels produced for high tensile purposes, where hardening and tempering is a normal item in process, copper may be considered as a useful element since its influence is analogous to that of nickel. Just as nickel-chromium steels are produced, so can copper-chromium steels be produced. From an industrial point of view copper does not seem to be a useful element to add in contents over 3 or 4 per cent.

The iron-copper system has been studied to some considerable extent, notably by Sahmen,[5] Ruer and Fick,[6] and Ruer and Goerens.[7] The work clearly demonstrates that iron may hold in solid solution a considerable percentage of copper. Those interested in the system should refer to the works mentioned.

§ (14) Silver (Group 1, Family B, atomic weight 107·93, melting-point 960·5° C.).—Alloys of iron and silver are not of industrial interest, but the iron-silver system has been studied.[8]

§ (15) Gold (Group 1, Family B, atomic weight 197·2, melting-point 1063° C.).—Gold is of no industrial interest as an added element in steels, but the iron-gold system has been studied.[9] Solid solutions are formed of gold in iron and iron in gold.

§ (16) Zinc (Group 2, Family B, atomic weight 65·4, melting-point 419·4° C.).—The relations of zinc to iron are of substantial interest as regards the galvanising process, and, whilst zinc can only be alloyed with iron

[1] *Stahl und Eisen*, xx. 837-844.
[2] *Zeits. für phys. Chem.* lxxvii. 591-613.
[3] *Comptes Rendus*, cliv. 592-594; 1913, clvi. 394-396.
[4] D. M. Buck, *Amer. Chem. Soc.*; *Jour. Industrial and Eng. Chem.*, 1913, v. 447-452; Clevenger and Ray, *Bull. Amer. Inst. of Mining Engrs.*, 1913, pp. 2437-2475; Cushman, *Bull. Am. Inst. of Mining Engrs.*, 1913, pp. 2936-2939.
[5] *Z. für anorg. Chem.* lvii. 1, 1908.
[6] *Ferrum*, 1913, xi. 39-51.
[7] *Ibid.*, Jan. 1917, xiv. 49-61.
[8] *Zeit. für anorg. Chem.* liii. 212.
[9] Isaac and Tammann, *Zeit. für anorg. Chem.* lv. 291-297.

with the greatest difficulty, and in the smallest proportions,[1] yet iron will alloy with zinc, and it is claimed that the compounds $FeZn_7$, $FeZn_3$, and probably Fe_3Zn, Fe_5Zn, and $FeZn_{10}$ may exist. It is of interest to note that galvanising baths which have remained for some months at a temperature just above the melting-point of zinc have been found to have crystals deposited in them which, on analysis, proved to contain 7·3 per cent of iron.[2] The iron-zinc system has not, apparently, been completely worked out.

There is evidence that in galvanising, where the zinc comes in contact with the iron, some diffusion occurs.

§ (17) Boron (Group 3, Family B, atomic weight 11, melting-point 2200-2500° C.).—Boron was for some time held to be an element which might be particularly useful for alloying with steel, and several investigators have contributed to our knowledge. Yensen[3] summarised the influence of the element as the result of his investigations; it would appear that boron acts very similarly to carbon. When present in substantial proportions, *i.e.* in similar proportions to carbon in steel, the effect is to harden up the alloy with the production of a higher tensile strength. The specific electrical resistance is increased by ·62 microhm per 0·1 per cent of boron combined with the iron. Yensen states that small additions of boron have a slightly beneficial effect upon the magnetic properties, probably owing to its action in reducing the oxide of iron which otherwise may be present in some instances, but this beneficial effect ceases after the smallest additions have been made.

The iron-boron and iron-boron-carbon systems have been studied by several investigators.[4] It would appear that in the iron-boron system the compound Fe_5B_2 is formed, and a similar system to the iron-carbide system results in which the Fe_5B_2 reacts in a similar manner to the Fe_3C. In this way the micro-constituents consist of a boride pearlite which, when quenched above the critical point, produces the boride solid solution.

Boron does not seem to be of much interest from the industrial point of view as an element for alloying with iron and steel. Practical experiments have been conducted[5] at Bitterfeld without any particularly encouraging results. When added to cast iron it would appear that the hardness is increased.

§ (18) Aluminium (Group 3, Family B, atomic weight 27·1, melting-point 658·7° C.).—Aluminium is a very useful element for adding to steel. In the first place, small percentages under ·02 per cent have a profound influence in preventing blow-holes in steel which would otherwise contain them. The explanation of this is not at the present time clear, but it would appear that the occluded gases which would otherwise come off during the freezing of the steel are retained in solution owing to the presence of the aluminium. In view of a recent theory on the cause of blow-holes, it may be that the addition of the aluminium had this action by destroying any oxide of iron which might otherwise be responsible for the evolution of carbon monoxide. The earlier statement, however, is, in the writer's opinion, most probably correct. This small addition of aluminium for the purpose of producing solid steel is also known to have a definite influence in reducing the tendency to segregation.[6] It is, however, necessary to record that the addition of small percentages of aluminium as above are apt to result in the oxide of aluminium, Al_2O_3, remaining in the steel, and, therefore, it is advisable to produce sound steel by the control of the furnace reactions rather than by the addition of aluminium.

The iron-aluminium system and the influence of aluminium on steel have been well studied.[7] Aluminium, when added to the iron-carbide series, reduces the solubility of carbide in iron and, generally speaking, acts in an analogous manner to silicon. The addition of the aluminium up to 6 per cent increases the hardness and strength of the material substantially as regards alloys with pure iron or low-carbon steel. It has a very beneficial effect on the magnetic properties when added in small quantities, Yensen finding that with ·40 per cent of aluminium the alloy annealed at 1100° C. had a maximum permeability above 35,000. The hysteresis loss for B max. = 10,000 and 15,000 is 450 and 1000 ergs per cm. per cycle respectively. For the higher aluminium contents the magnetic quality decreases. It is suggested that the hysteresis loss with the best aluminium alloys is much less than in the case of 3·5 per cent high permeability commercial silicon steel, which is discussed elsewhere. The specific electrical resistance increases about 12 microhms for each per cent of aluminium added until the amount exceeds 3 per cent, when the rate

[1] S. Wologdine, *Revue de Métallurgie*, iii. 539-546.
[2] E. Vigouroux, F. Ducelliez, and A. Bourbon, *Bull. Soc. Chim. de France*, 1912, No. 10, pp. 11-12; *Chem. News*, July 19, 1912, cvi. 36.
[3] *Univ. of Illinois Bull.*, March 22, 1915, Bull. No. 77, No. 29, xii.
[4] Tschischewsky and Herdt, *Revue de la Société russe métallurgique*, 1915, i. 533-546; Hannesen, *Zeits. f. anorg. Chem.*, Nov. 5, 1914, lxxxix. 257-278; Iwai and Ballagh, *Mining and Scientific Press*, August 7, 1909.
[5] Electro-Chemical Works, Bitterfeld, *Stahl und Eisen*, 1914, xxxiv. 1530-1531.
[6] Benjamin Talbot, *Iron and Steel Inst. Jour.*, 1905, No. 2, p. 218; *Amer. Mining Engrs.*, April 24, 1914, xxxiii. 391-392.
[7] R. A. Hadfield, *Iron and Steel Inst. Jour.*, 1890, ii. 161; Yensen and Gatward, *Univ. of Illinois Bull.*, Jan. 1917, No. 95 (54 pp.).

of increase falls off gradually. It will be seen from these remarks that the addition of aluminium in considerable amounts may serve a useful purpose, but it has to be borne in mind that there are difficulties—excessive shrinkage, etc.—which must be dealt with suitably before such steels can be satisfactorily employed. To date, little use appears to have been made industrially of aluminium as an alloying element in steel.

§ (19) Zirconium (Group 4, Family A, atomic weight 90·6, melting-point 1700° C.).—Much has been written relative to the influence of zirconium on steel, but almost invariably the data are of a non-quantitative type. It may be considered that there are no published investigations which enable us to form a definite estimate of the influence of this element.

§ (20) Titanium (Group 4, Family A, atomic weight 48·1, melting-point 1900° C.).—Many claims have been made for the influence of this element upon steel and iron, but its actual influence can be stated as follows. The element titanium has a great affinity for oxygen, and therefore, when added to molten steel, acts as a deoxidiser, and is to some extent used for this purpose. As regards the mechanical properties of steel it is established that titanium has little advantageous influence, whilst as regards general properties it is claimed that the addition of the element causes a decrease of hysteresis and an increase of permeability if the addition is up to 1 per cent, after which percentage the reverse influence sets in. Guillet[1] made a study of titanium steels containing titanium up to 10 per cent,[2] and came to the conclusion that the element has no appreciable influence on the mechanical properties, and that the whole range of the steels are pearlitic. Vogel[3] came to a slightly different conclusion from Guillet. The electrical properties have been studied by Hunter and Bacon.[4] There is much literature concerning the influence of this element which may be disregarded.

§ (21) Carbon (Group 4, Family B, atomic weight 12·0, melting-point 3600° C.).—This element is the essential element in steel. Without carbon, iron loses that distinctive property of effectively hardening when quenched from high temperatures. The influence of carbon is, however, dealt with elsewhere.[5]

§ (22) Silicon (Group 4, Family B, atomic weight 28·4, melting-point 1420° C.).—Silicon is one of the few valuable elements used for alloying with steel. Its influences are several. Perhaps the most important feature is its influence in producing sound steel, *i.e.* steel which is free from blow-holes. Silicon added for this purpose has a similar action to aluminium, but in less degree, since the element combines with any oxygen in the steel, forming SiO_2, which, given temperature and time, rises to the surface of the steel. In the acid open-hearth process, during the last stages of the refining operation, silicon is reduced from the slag and returns into the metal, thus deoxidising it and producing a steel which will pour solid. Silicon is also added in percentages round about 1 per cent, sometimes upwards of that figure, in different alloy steels which are to be hardened and tempered, there being evidence to show that the toughness of the material in the final stages thereby improves. One important feature of the use of a high silicon is in high-permeability steel, which is a very low carbon steel to which has been added 3 to 4 per cent of silicon. Silicon substantially reduces the hysteresis loss. It is also of interest to note that alloys of iron and silicon containing 15 per cent of silicon are acid-resisting. As regards the physical chemistry and metallurgy of the iron-silicon and iron-silicon-carbon alloys, much work has been done which might usefully be studied by those interested.[6]

§ (23) Tin (Group 4, Family B, atomic weight 119, melting-point 231·9° C.).—The use of tin in the steel industry is in the manufacture of tin-plates, a most interesting process conducted largely in South Wales. Apparently slight diffusion takes place between the steel and the tin at the surface of contact.

The iron-tin system has been studied by Isaac and Tammann.[7] L. Guillet[8] produced two series of steels, one containing carbon 0·1–0·20 per cent with tin 1·79–9·98 per cent, the other series with a carbon content of 0·66–0·76 per cent with tin ranging from 2·05 to 9·75 per cent. None of the alloys except one containing 0·76 per cent carbon and 2·05 per cent of tin were capable of being forged. He came to the conclusion that the influence of tin was similar to that of titanium and silicon. However, tin as an element for alloying with steels is not of much interest from the industrial point of view, its only

[1] L. Guillet, *Revue de Métallurgie*, 1905, pp. 350-367.
[2] *Jour. Iron and Steel Inst.*, 1906, No. 2, p. 18.
[3] *Ferrum*, 1917, xiv. 177-197.
[4] *Amer. Electrochem. Soc.*, April 8, 1920.
[5] See § (1); also article "Iron-carbon Alloys."

[6] Charpy and Cornu-Thenard, *J. Iron and Steel Inst.*, 1915, No. 1, p. 276; Guertler and Tammann, *Zeit. für anorg. Chem.* xlvii. 163; P. Paglianti, *Metallurgie*, ix. 217-230; E. Vigouroux, *Comptes Rendus*, May 5, 1913, clvi. 1374-1376; Charpy and Cornu, *Comptes Rendus*, April 21, 1913, clvi. 1240-1243; Gumlich and Goerens, *Faraday Society*, October 1912; S. Guggenheim, *Schweiz. Elektrot. Verein Bull.*, 1910, No. 3, i. 88-114; Burgess and Aston, *Metallurgical and Chem. Eng.*, March 1910, viii. 131-133; Gontermann, *J. Iron and Steel Inst.*, 1911, No. 2; Portevin, *J. Iron and Steel Inst.*, 1909, No. 1, Carnegie Schol. Memoirs; Guillet, *J. Iron and Steel Inst.*, 1906, No. 2; T. Baker, *J. Iron and Steel Inst.*, 1903, No. 2; Sir Robt. A. Hadfield, *J. Iron and Steel Inst.*, 1889, No. 2.
[7] *Zeits. für anorg. Chem.* liii. 281-290.
[8] *Revue de Métallurgie*, 1904, pp. 500-505.

interest lying in the metal as a coating in the manufacture of tin sheets mentioned above.

§ (24) VANADIUM (Group 5, Family A, atomic weight 51·2, melting-point 1730° C.).—There is much literature relative to the influence of vanadium, but its usefulness may be placed under two headings. Like several other elements its great affinity for oxygen renders it useful as a deoxidiser, and in some works small percentages are added for this purpose. Its great use in steel metallurgy, however, arises from the fact that it is considered to increase the resistance of steels to fatigue. It is also a constituent of high-speed tool steels, since its addition is claimed to result in the production of high-speed tools capable of doing heavier work. Portevin's researches [1] indicated that the addition of vanadium was responsible for raising the temperature of the carbon change-point. The iron-vanadium system has been thoroughly studied by Vogel and Tammann.[2] The ternary system iron-vanadium-carbon has not had much attention, but a number of alloys were studied by Arnold and Read,[3] as a result of which investigations evidence was forthcoming that the vanadium formed a carbide, V_4C_3. The writer's own investigations have also pointed to the fact that vanadium enters largely into the carbide constituent. A number of researches deserve the attention of any one particularly interested in the influence of this element, notably those of Arnold,[4] Sankey and Kent Smith,[5] Guillet,[6] and McWilliam and Barnes.[7]

§ (25) TANTALUM (Group 5, Family A, atomic weight 181, melting-point 2850° C.).—There is only scanty evidence as to the influence of tantalum when alloyed with iron and steel. Some work has been done by Guillet [8] and Breuil.[9] Guillet added percentages of tantalum varying from 0·09 to 1·05 per cent to steels containing carbon 0·12–0·18 per cent. The presence of the element appears to raise the strength of the material and at the same time to reduce the ductility. As to the effect of tantalum upon the general physical properties, evidence does not appear to be available.

§ (26) NITROGEN (Group 5, Family B, atomic weight 14·01, melting-point −210° C.).—It has frequently been suggested that nitrogen has a deleterious influence upon irons and steels in the quantities present in such commercial products. Nitrogen is present in steel invariably, but only in small quantities ranging from ·002 to ·015 per cent. There is no evidence extant to show that the variation in nitrogen within these limits has any influence upon steels, and the influence of the element may, therefore, be disregarded. Any one particularly interested in the influence of this element will find a relatively large literature dealing with it.[10]

It should always be remembered that Bessemer steel is manufactured by blowing atmospheric air through molten iron, and, therefore, there is every opportunity for nitrogen to be taken up by the metal. In practice it is found that Bessemer steels contain more nitrogen than any other class of steel, but within the limits mentioned above, and we have definite evidence that such steels are not noticeably affected by such content.

§ (27) PHOSPHORUS (Group 5, Family B, atomic weight 31·0, melting-point 44° C.).—This element is present as an impurity in all irons and steels. It is generally present in percentages varying from 0·01 to 0·06 per cent. If a much higher phosphorus content is introduced the influence of the phosphorus is to harden up the steel, increase the tensile strength, and reduce the ductility. It is claimed that the electrical resistance increases in proportion as the phosphorus increases. Steel manufacturers have always looked upon phosphorus as being an element of which they prefer to have as little as commercial considerations will permit in the best steels, and the writer knows of no data which would support a contrary view. There is a large literature on the subject to which reference can be made.[11]

§ (28) ARSENIC (Group 5, Family B, atomic weight 75·0, melting-point 850° C.).—Arsenic alloys with iron, and is usually found in very small quantities in most irons and steels. At one time it was thought to have a deleterious influence on the material, but investigations have shown that very small percentages have little influence. K. Friedrich [12] has studied a series of alloys and sketched, in a preliminary manner, the iron-arsenic system. The compounds Fe_2As, Fe_3As_2, and FeAs are

[1] Carnegie Memoirs, *Iron and Steel Inst.* i.
[2] *Zeits. f. anorg. Chem.*, May 6, 1908.
[3] *J. Iron and Steel Inst.*, 1912, No. 1.
[4] *Ibid.*, 1915, No. 1.
[5] *Proc. Inst. Mech. Engrs.*, 1904.
[6] *Revue de Mét.* iv. 775-783.
[7] *J. Iron and Steel Inst.*, 1911, i.
[8] *Comptes Rendus*, cxlv. 327.
[9] *Génie civil*, xiv. 7 and 25.

[10] Grabe, *Revue de Métallurgie*, v. 353-354; Wust and Sudhoff, *Metallurgie*, vii. 257-261; Braune, *Jernkontorets Annalen*, lix. 656-762; Pourcel, *Revue universelle des Mines*, xv. pp. 229-236; Stromeyer, *Jour. Iron and Steel Inst.*, 1909, lxxix. 404-420; Andrew, *Jour. Iron and Steel Inst.*, September 1912; *Metallurgical and Chemical Engineering*, 1913, xi. 121-122; Tschischewski, *Jour. Iron and Steel Inst.*, Autumn 1915; Wheeler, *Amer. Inst. Mining Engrs.*, April 1920, No. 160, Section 4; Comstock and Ruder, *Chem. and Met. Eng.*, 1920, xxii. 399-405.

[11] Arnold, *Jour. Iron and Steel Inst.*, 1894, i.; Stead, *Jour. Iron and Steel Inst.*, 1900, ii.; Saklatwalla, *Jour. Iron and Steel Inst.*, 1908, ii.; D'Amico, *Ferrum*, 1913, x. 289-304; Stead, *Jour. Society Chem. Industry*, Feb. 28, 1914; W. H. Hatfield, *Jour. Iron and Steel Inst.*, 1915, No. 2; D'Amico, *Metallurgia italiana*, 1917, ix. 142-152; Stead, *Jour. Iron and Steel Inst.*, 1918, i. 389; J. S. Unger, *Amer. Iron and Steel Inst.*, 1918, 172-193; Gercke, *Metallurgie*, v. 604-609.

[12] *Metallurgie*, iv. 129-137.

suggested with Fe_2As as a constituent of an eutectic with a freezing-point of about 830° C. Further work has been published by Burgess and Aston;[1] these workers state that iron readily takes up 4 per cent of arsenic, and that such material can be forged.

J. Liedgens[2] has studied the influence of arsenic from the steel production point of view. He cast a number of ingots containing from 0·123 to 3·515 per cent of arsenic, and claims to show that the increase of arsenic increases the specific gravity and the specific resistance of the metal. Permeability, hysteresis loss, and coercive force are generally favourably influenced. The writer agrees with the last worker that arsenic is not to be regarded as a dangerous constituent in steel when present in small quantities, but, on the other hand, its presence does not materially increase any useful property.

§ (29) Antimony (Group 5, Family B, atomic weight 120·2, melting-point 630° C.).—Antimony readily alloys with iron and forms the iron-antimony system, which has been studied by A. M. Portevin,[3] Kurnakow and Konstantikow,[4] and Goerens and Ellingen.[5] Thermo- and metallographic work has been done on the different alloys, but little data have apparently been obtained relative to the influence of antimony upon the useful properties of steels. The influence of the element upon the carbon change-point would appear to be that of raising it some 60-70°, with antimony present in quantities ranging from 1 to 9 per cent.

§ (30) Bismuth (Group 5, Family B, atomic weight 208, melting-point 271° C.).—Little work has been done in connection with the influence of this element upon steel. It forms a series of alloys which have been partially studied by Burgess and Aston.[6] It has not been used commercially as a constituent of steels within the writer's experience. The investigators to whom reference has just been made suggest that a 2 per cent bismuth alloy gives a high magnetic density value.

§ (31) Chromium (Group 6, Family A, atomic weight 521, melting-point 1510° C.).—Chromium is perhaps the most valuable element of all for alloying with steel, since after carbon, which is an essential constituent, there is no element whose action is so great in modifying the mechanical and physical properties of the resultant material. Chromium increases the hardness of structural steels in the normalised condition. It renders possible the hardening of thicker section than is possible with carbon steel, owing to its effect upon the solubility of carbide in iron, thus enabling hardened and tempered steel to be produced of considerable thicknesses.

Chromium, when added to iron and steel, also increases its resistance to corroding media, the richer alloys being resistant to various acids according to the actual composition. The well-known stainless steel is an alloy of 12-14 per cent of chromium. Chromium increases the value of steel as permanent magnets and, incidentally, decreases the magnetic permeability.

The effect of chromium is definite as regards the position of the carbon change-point, since it definitely raises the temperature at which the solid solution breaks down. So considerable is its effect that steels with the higher content of chromium have to be quenched at as much as 100° and 200° C. above the temperature for ordinary carbon steels. An interesting feature from this point of view is that the magnetic change remains constant in position, and, if a specimen of chromium steel is heated, is frequently observed to take place below the carbon change-point. Steels with much chromium present are air-hardening steels, *i.e.* ordinary rates of cooling in air are sufficient to cause a partial suppression of the resolution of the solid solution into its products. It has been definitely established that when chromium is added to steel a considerable proportion of the chromium is to be found associated with the carbide as a carbide of chromium. Thus the carbide in such steels, instead of being carbide of iron, is really what may be described as a double carbide of iron and chromium. The effect of the presence of chromium is to increase the solubility of carbon in iron. Chromium steels have been studied by many investigators. The iron-chromium system has been studied by Jänecke,[7] and an equilibrium diagram sketched. This work is apparently an advance upon an earlier attempt.[8] The iron-carbon-chromium system has been studied by many investigators,[9] and much work has

[1] *American Electrochemical Society's Transactions*, xv. 369-386.
[2] *Stahl und Eisen*, 1912, xxxii. 2109-2115.
[3] *Revue de Métallurgie, Mémoires*, viii. 312-314; *Carnegie Memoirs*, i. 383.
[4] *Zeits. für anorg. Chem.*, 1908, lviii. 1-22.
[5] *Metallurgie*, vii. 72-79.
[6] *American Electrochemical Society's Transactions*, xv. 369-386.
[7] *Zeits. für Elektrochemie*, Feb. 1, 1917, pp. 49-55.
[8] Treitschke and Tammann, *Zeits. für anorganische Chemie*, 1907, lv. 402-411.
[9] Osmond, *Jour. Iron and Steel Inst.*, 1890, i.; R. A. Hadfield, *Jour. Iron and Steel Inst.*, 1892, ii.; Guillet, *Revue de Métallurgie, Mémoires*, 1904, i.; Giesen, *Jour. Iron and Steel Inst.*, Carnegie Scholarship Memoirs, 1909; McWilliam and Barnes, *Jour. Iron and Steel Inst.*, 1910, i.; Arnold and Read, *Jour. Iron and Steel Inst.*, 1911, i.; Portevin, *Comptes Rendus*, July 3, 1911, cliii. 64-66; M. B. Moir, *Phil. Mag.*, November 1914, xxviii. 738-748; Dupuy and Portevin, *Jour. Iron and Steel Inst.*, 1915, i. 306; Edwards and Kikkawa, *Jour. Iron and Steel Inst.*, 1915, No. 2, pp. 6-30; T. Murakami, 24th Report of the Alloys Research Inst., *Sci. Report Tohoku Imp. Univ.*, 1918, vii. 217-276; Portevin, *Revue de Métallurgie, Mémoires*, viii. 802-803; F. Cirkel, Canada Dept. of Mines, Ottawa; Goerens and Stadeler, *Metallurgie*, iv. 18-24.

been done on the physical properties of such alloys and steels.

§ (32) TUNGSTEN (Group 6, Family A, atomic weight 184, melting-point 3000° C.). —Tungsten is a valuable element in the metallurgy of special steels. Its essential uses are in the production of high-speed steel, where the combined influence of tungsten and chromium induces the properties well known in high-speed tools, and which will be discussed elsewhere, and in magnet steels, which are also treated in detail elsewhere.

Comparatively little experimental work has been done. The iron-tungsten system has been partially investigated by Harkort,[1] who came to the conclusion that a tungstide of iron, Fe_3W, is an essential constituent of the alloys containing over 20 per cent of tungsten. The tungsten-carbon series has been studied by Ruff and Wunsch.[2] As regards the iron-carbon-tungsten system there is a fair amount of experimental work, beginning with Sir Robert Hadfield's research.[3] This was followed by an interesting research by Guillet.[4] The addition of tungsten increases the strength of steels, but, as brought out by Dr. T. Swinden in his extremely valuable research,[5] the essential value of tungsten lies in its property of modifying the position of the phase change temperatures. It is an interesting fact that tungsten steel, if heated to temperatures of 850°-900° C., has a carbon change-point at a similar temperature to that in carbon steels, whereas if such steels are heated to a substantially higher temperature the change-point is considerably depressed. In this original discovery of Swinden's lay the ultimate explanation of the properties of the high-tungsten high-speed steels, which will be dealt with under separate heading. A further paper by Swinden[6] is well worth studying. An attempt to determine the distribution of the tungsten amongst the constituents of steel was made by Arnold and Read.[7] This work, however, was inconclusive. Reference might also be made to other investigations.[8]

§ (33) MOLYBDENUM (Group 6, Family A, atomic weight 96, melting-point 2500° C.).— This element is similar to tungsten in its influence upon steel. It is valuable as a constituent of tool steels, particularly high-speed tool steels, and magnet steels.

The iron-molybdenum system has been studied by Lautsch and Tammann,[9] and a diagram roughly drawn. Much further work, however, requires to be done in this field.

The iron-carbon-molybdenum steels have been studied by several investigators, to whose work reference may be made.[10]

§ (34) URANIUM (Group 6, Family A, atomic weight 238·5, melting-point (?—not known)).— There is as yet no published evidence as to the utility of this element as a useful addition to steel. It has been claimed that it is useful in tool steels. A statement on the preparation of ferro-uranium has been issued.[11]

§ (35) OXYGEN (Group 6, Family B, atomic weight 16·00, melting-point −218° C.). — In discussing the presence of oxygen in steel we must consider that portion which is uncombined with carbon, *i.e.* is present in solution as carbon monoxide, and must ignore that which is in combination in the so-called slag inclusions as oxides of manganese and silicon, iron, etc. The writer considers that the balance of oxygen remaining in properly made steel after such deductions is *nil*, and holds that there are no substantial data existing to controvert that point of view. If steel is over-oxidised during manufacture and is not properly "killed" by the use of suitable deoxidisers, it seems feasible that ferrous oxide will be present in solution in the molten steel. The system FeO-Fe has not apparently been investigated. Any one interested will find a large literature dealing with this element.[12] The total oxygen content, whatever may be the form in which it is present, is not considered to exceed 0·01 per cent in commercial products.

§ (36) SULPHUR (Group 6, Family B, atomic weight 32·06, melting-point 106·8°-119·2° C.). —This element is present in irons and steels

[1] *Metallurgie*, iv. 216-224, 225-241.
[2] *Zeits. für anorg. Chem.*, 1914, lxxxv.
[3] *Jour. Iron and Steel Inst.*, 1903, ii. 14-76.
[4] *Revue de Métallurgie*, 1904, pp. 263-283.
[5] *Jour. Iron and Steel Inst.*, 1907, i. 291-324.
[6] *Ibid.*, 1909, ii. 223-252.
[7] *Inst. of Mech. Engrs.*, March 1914.
[8] Guillet, *Revue de Métallurgie*, 1905, pp. 350-367; Portevin, *Jour. Iron and Steel Inst.*, 1909, No. 1; Giesen, *Jour. Iron and Steel Inst.*, Carnegie Scholarship Memoirs, 1909, i.; Dupuy and Portevin, *Jour. Iron and Steel Inst.*, 1915, i. 320-321; Honda and Murakami, *Tôhoku Imp. Univ. Science Reports*, April 1918, vi. 235-283.
[9] *Zeits. f. anorg. Chem.*, October 12, 1907, lv. (4) 386-401.
[10] Guillet, *Revue de Métallurgie*, 1905, p. 350; Carpenter, *Jour. Iron and Steel Inst.*, 1905, i. 433; T. Swinden, *Jour. Iron and Steel Inst.*, Carnegie Schol. Mems., 1913, v. 100-168; Newton Friend and Marshall, *Jour. Iron and Steel Inst.*, May 1914; Dupuy and Portevin, "Thermo-Electric Props. of Special Steels," *Jour. Iron and Steel Inst.*, 1915, No. 1, p. 306; Arnold and Read, *Inst. Mech. Engrs.*, December 1915; Aitchison, *Chem. Soc. Trans.*, Nov. 1915, cvii. 1531-1538; Sir Robt. Hadfield, *Inst. Mech. Engrs.*, 1915, pp. 701-713.
[11] U.S. Bureau of Mines, 1917, *Tech. Paper*, 177, H. W. Gillett and E. L. Mack.
[12] Zyremski, *Stahl und Eisen*, 1884, p. 536; Cubillo, *Jour. Iron and Steel Inst.*, 1903, i.; Belloc, *Revue de Métallurgie*, 1908, p. 469; Goutal, *Comptes Rendus*, 1909, cxlviii.; McMiller, *Met. and Chem. Eng.*, 1913, xi. 86; Pickard, Carnegie Schol. Mems., *Iron and Steel Inst. Jour.*, 1913; Pickard and Potter, *Jour. Iron and Steel Inst.*, 1914; Austin, *Jour. Iron and Steel Inst.*, Autumn 1915; Pickard, *Jour. Iron and Steel Inst.*, Carnegie Schol. Mems., 1916, pp. 68-82; Smits and Bijvoet, *Amsterdam, Proc. Acad. Sci.*, 1919, xxi. 386-400.

as an impurity, and the steel-maker's object is always to reduce the sulphur content of the steel to as low a value as manufacturing conditions will permit. It is usually present in quantities ranging from 0·01 to 0·06 per cent. Abnormally high sulphur is a bad feature, since the sulphur is present in combination with manganese as sulphide of manganese. Sulphide of manganese is insoluble in the steel, and occurs as a separate, hard, brittle constituent, and therefore, as such, is an added weakness to the steel when under stress. Much work has been done on the manner in which sulphur occurs in steel, and also upon its influence, and the records may be studied by those interested.[1]

§ (37) MANGANESE (Group 7, Family A, atomic weight 55·0, melting-point 1225° C.).—This element may be considered in small quantities to be an essential constituent of steels. It is the most important and most generally used deoxidiser, and as such its use converted the original unsuccessful Bessemer process into the first successful process for what may be considered the mass production of steel. Manganese has greater affinity for oxygen than iron, and thus combines with any oxygen present to form manganous oxide, MnO. Another important influence is its effect upon sulphur.[2] Most ferrous raw materials contain more or less sulphur, and it is found that manganese unites with the sulphur, causing the sulphur to be present as globules of manganese sulphide[3] instead of as somewhat dangerous films of sulphide of iron, FeS. Thus it will be found that commercial steels are made to contain anything up to 1 per cent of manganese for the purpose of ensuring that any oxygen or sulphur present is suitably dealt with. Incidentally, the presence of this manganese has a materially strengthening effect upon steel, since it raises the hardness and tensile strength without unduly affecting the ductility.

It was early found that when much more than 1 per cent of manganese was present the effect appeared to be deleterious, as, for instance, when 2½ per cent of manganese was added the material in the ordinary forged condition appeared to be brittle. Sir Robert Hadfield, however, in the 'eighties, courageously proceeded with experiments with still higher manganese content, and discovered the famous manganese steel,[4] which contains 12-14 per cent of manganese, and has become a steel product of considerable industrial importance. This material, whilst extremely hard in the cast condition, if quenched from high temperatures possesses physical properties which at the time of their discovery were quite new in the metallurgy of steel. In the water-toughened condition such material may have, with a tensile strength of 60 tons per square inch, a ductility which is responsible for an elongation as high as 50 per cent. Such steel can be bent double, and it was further found in this water-toughened condition to be non-magnetic. Hadfield's manganese steel contains upwards of 1 per cent of carbon. Of late years the manufacture of low carbon ferromanganese has made possible the production of intermediate steels between the manganese steel and the ordinary steel which also contained low-carbon contents, and such steels are of commercial interest. Manganese, when present in steel, is to a considerable extent in combination with the carbide as a double carbide of iron and manganese.[5]

The iron-manganese system has been studied by Levin and Tammann and Rumelin and Fick,[6] and the diagram sketched. With increase in manganese content the freezing-point of the alloy is dropped. Incidentally, the addition of the manganese has a profound effect on lowering the critical points, with the effect that the percentage of manganese is soon attained at which the alloy persists in the gamma condition at ordinary temperatures. Lutke has studied the effect of manganese upon the iron-carbon system.[7] There are many valuable researches extant dealing with the influence of manganese on the iron-carbon system from different points of view, to which the reader should refer.[8]

§ (38) COBALT (Group 8, atomic weight 59·0, melting-point 1490° C.).—This element is being used in steel metallurgy as a constituent of steels. Its use was first brought to the public notice as a constituent of high-speed steels, but has been further extended to magnet steels and some of the more expensive high-

[1] Stead, *Staffordshire Iron and Steel Inst.*, March 1908; Ziegler, *Revue de Métallurgie*, 1909, p. 459; D. M. Levy, *Staffordshire Iron and Steel Inst.*, February 1910; K. Friedrich, *Metallurgie*, May 1910, vii. 257-261, Loebe and Becker, *Zeits. für anorganische Chemie*, 1912, lxxvii. 301-319; J. S. Unger, *Iron Age*, 1916, xcvii. 146-150; E. Becker, *Stahl und Eisen*, xxxii. 1017-1021.

[2] Levy, *Staffordshire Iron and Steel Inst.*, 1909–1910; Rohl, *Jour. Iron and Steel Inst.*, Carnegie Schol. Mem., 1912, iv.

[3] R. A. Hadfield, *Jour. Iron and Steel Inst.*, 1893, No. 2.

[4] See "Manganese Steel."

[5] Arnold and Read, *Jour. Iron and Steel Inst.*, 1910, i. 169.

[6] *Ferrum*, 1914–15, xii. 41-44.

[7] *Metallurgie*, May 8, 1910, vii. 268-273.

[8] F. Osmond, *Jour. Iron and Steel Inst.*, 1887, No. 2, pp. 343-344; Stead, *Jour. Iron and Steel Inst.*, 1894, xlv. 193; Guillet, *Jour. Iron and Steel Inst.*, 1905, No. 2; E. Griffiths, *Inst. Electrical Engrs. Jour.*, Sept. 1911, xlvii. 771-778: Arnold and Knowles, *Jour. Iron and Steel Inst.*, October 1911; W. H. Hatfield, *Proc. Royal. Soc.* A, 1911, lxxxv.; Sir Robt. Hadfield, *Jour. Iron and Steel Inst.*, Sept. 1913; W. S. Potter, *Amer. Inst. of Mining Engrs.*, February 1914; Hadfield and Hopkinson, *Jour. Iron and Steel Inst.*, May 3, 1914; Dupuy and Portevin, *Jour. Iron and Steel Inst.*, 1915, No. 1, p. 306; Howe, *Amer. Soc. for Testing of Materials*, June 1917; Matsushita, *Science Reps. Tôhoku Imp. Univ.*, 1919, viii. 79-88.

tensile steels. Guillet [1] experimented with the influence of cobalt on steel, and found that the close resemblance which existed between the elements nickel and cobalt was not reflected in their relative influence on steel. The Japanese have of late discovered alloys rich in cobalt, which have particularly good properties as permanent magnets, but such alloys cannot be considered as steels.

The iron-cobalt system has been studied by Ruer and Kaneko [2] and Guertler and Tammann.[3] The cobalt-carbon system has been studied by G. Boecker.[4] The iron-carbon-cobalt system has not been much studied hitherto. For further information reference should be made to sundry papers to which reference is here given.[5]

§ (39) Nickel (Group 8, atomic weight 58·7, melting-point 1452° C.).—This element is an extremely important one as a constituent in many alloy steels. It was early found that nickel added to carbon steels raised the hardness and tensile strength without unduly decreasing the ductility. With the introduction, however, of hardening and tempering of steel in fairly large masses, it was found that nickel has a valuable influence by assisting in the hardening through of increasingly heavy sections, thus enabling a finally hardened and tempered steel to be made of high quality. This aspect will be dealt with later. The iron-nickel steels containing high percentages of nickel are of particular interest, the 25 per cent nickel steel being excellent for rust resisting, whilst the well-known "Invar" metal contains a still higher percentage.[6] Nickel steels are an extremely interesting series, and reference should be made to several valuable researches extant.[7]

§ (40) Platinum (Group 8, atomic weight 194·8, melting-point 1755° C.).—It is of interest to record that the iron-platinum system has been studied by Isaac and Tammann.[8] They claim that at high temperatures iron and platinum form an uninterrupted series of mixed crystals.

[1] *Revue de Métallurgie*, 1905, p. 348.
[2] *Ferrum*, 1913–14, xi. 33-39.
[3] *Zeitschrift für anorganische Chem.* xlv. 205 and 224.
[4] *Metallurgie*, May 8, 1912, ix. 296.
[5] Kalmus and Blake, *Amer. Inst. Chem. Eng.*, January 1917; Guillet, *Jour. Iron and Steel Inst.*, 1906, No. 2, p. 18.
[6] See "Invar and Elinvar."
[7] L. Guillet, *Revue de Métallurgie*, 1905, pp. 350-367; G. B. Waterhouse, *Iron Age*, 1906, lxxvii. 490-491; E. Preuss, *Iron and Steel Inst.*, Carnegie Schol. Mems., 1909, i. 60-142; Burgess and Aston, *Met. and Chem. Eng.*, January 1910, viii. 23-26; Arnold and Read, *Inst. Mech. Engrs.*, March 20, 1914; Chevenard, *Revue de Métallurgie, Mémoires*, 1914, xi. 841-862; Dupuy and Portevin, *Jour. Iron and Steel Inst.*, 1915, No. 1, p. 306; Yensen, "Mining and Metallurgy," *Amer. Inst. Mining and Metl. Engrs.*, January 1920, No. 157, Section 9; Guillaume, *L'Électricien*, xxxviii. 55; Riley, *Jour. Iron and Steel Inst.*, 1889, i. 45; Hadfield, *Inst. Civil Engrs.*, 1899.
[8] *Zeitschrift für anorganische Chemie*, lv. 63-71.

III. The Heat Treatment of Special Steels

The heat treatment of carbon steels is dealt with elsewhere.[9] In considering special steels, however, it is necessary that some reference should be made to the simpler carbon steels. Under this heading it is proposed to deal with normalising, annealing, hardening, and tempering.

§ (41) Normalising. — By normalising we mean heating a steel (however previously treated) to a temperature exceeding its upper critical point and allowing it to cool freely in the air. The temperature should be maintained for some little time at this maximum temperature, which should not exceed the upper limit of the critical range by more than 50° C. If this treatment is applied to carbon steels the effect of previous treatment is removed. If the condition of the material had been that of a coarse-grained structure resulting from heating to high temperatures, or if the pearlite has become globularised through maintenance at relatively low temperatures, such structures are replaced by a uniform structure consisting of normal-sized grains with the pearlite of a reasonably fine structure. In this condition, therefore, the steels may be considered to be in a most consistent and reliable state, and the mechanical properties corresponding to such conditions are stated in Table 1. With alloy steels, however, the problem becomes different, since, if nickel-chromium and other elements are present, the mobility of the change from solid solution is reduced and the cooling in air provides a sufficiently rapid quenching effect to lead, to a varying extent, to the hard condition of the particular steel. It will thus be seen that if alloy steels are normalised the result is, generally speaking, very different from what it is in the case of carbon steels. Normalising, in the ordinary sense, is not used with these steels, but still it is found that a comparable treatment interposed between the rolling or forging of the steel and the subsequent heat treatment does sometimes lead to an improvement in the ultimate condition of the material.

§ (42) Annealing.—The term annealing is synonymous in most minds with that of softening, and, indeed, that is the best description of what is meant. Annealing consists of reheating to a predetermined temperature, maintenance at that temperature for a certain length of time, usually followed by slow cooling. Owing to the variable composition of the different special steels, varying treatments are employed. For instance, with some special steels which require to be annealed, particularly rich in the added elements, the cooling must be very slow if a complete

[9] See "Iron-carbon Alloys."

softening is to be obtained. In such cases it is best to anneal at temperatures below the carbon change-point, and thus to produce the annealing effect by a complete tempering treatment. On the other hand, where the added elements have not the same pronounced effect in modifying the speed of translation from the solid solution state, it is found the most practicable to heat the material to above the upper critical point as in the case of normalising, and then allow the steel to cool down in the furnace, *i.e.* very slowly.

Annealing is generally introduced for the purpose of making the steel soft enough to machine with ease, for which purpose in the case of alloy steels Brinell hardness numbers should be produced as near as possible to 200. The treatment is, however, resorted to, particularly in steel castings, for the purpose of removing internal stresses, for which purpose relatively low temperatures only are needed, or entirely to refine the crystalline structure, in which case the upper critical point must be exceeded as in the case of normalising.

It will be appreciated, however, that each separate steel requires its own special temperature, but elsewhere in this article will frequently be found guiding temperatures and particulars for the different steels now utilised in the industrial arts.

§ (43) HARDENING. — Hardening is an extremely important treatment when the alloy steels are considered. If the alloy steels are being used for the sake of the superior mechanical properties, it is essential that a satisfactory hardening of the mass shall be obtained prior to the tempering operation, as otherwise the latter treatment is applied to an unsatisfactory condition of the steel, which will result in a final condition in which the properties of the material will be deficient. In hardening any steel, carbon, or alloy steel, it is necessary that the upper critical point shall have been passed. Below the upper critical point the steel is not a simple substance, but consists more or less of the ferritic or iron matrix in which the pearlite or solid solution areas occur, and quenching from such temperatures produces steel which is not homogeneous in structure. If the upper critical point is exceeded and the steel maintained at such temperatures for some time, equilibrium for the temperature is attained, and a simple condition of solid solution results. This is the condition in which the steel should be at the moment it is quenched either in water or oil. In ordinary carbon steels quenching as drastically as possible in water results, in the case of thin sections, in the attainment of the completely hard condition of the steel. With increasing size of mass, owing to the rapidity with which the solid solution will break down into pearlite, the interior of such masses in carbon steel consists of the decomposition products from the solid solution, and is, therefore, not completely hardened. If we now consider the steel containing, say, 1-2 per cent of chromium, or 3 per cent of nickel and 0·5–1·0 per cent chromium, we find that in a reasonably large mass, 2 or 3 inches in section, the addition of these elements has rendered it possible for the hard condition of the material to be attained throughout the mass. If it is desired to harden yet larger sections, then it is necessary still to burden the steel with higher percentages of nickel and chromium so that the sluggishness of the change from solid solution to the soft condition is still further increased. Here we have, as regards the alloy steels used for structural purposes, the essential reason for the advantageous results obtained after heat treatment.

In some of the alloy steels it is found that too drastic quenching, as in the case of water-quenching, results in the creation of internal stresses which frequently smash the parts, particularly if they are complicated in design, and it is found necessary, therefore, to harden in oil. Although hardening in oil results in a slower speed of cooling, the presence of the added elements still enables a satisfactorily hard condition of the material to be attained. It will thus be seen that here is another advantageous influence of the added elements.

One very interesting type of steel now used on a considerable scale is the air-hardening type, which is burdened with a sufficient percentage of nickel and chromium or of chromium to enable the steel to retain a satisfactory state of hardness even after cooling in air.

Fracture from internal stresses as a result of the hardening operation must be carefully prevented. In the first place the steels must be perfectly sound and free from defects, and then it is also necessary, in the case of alloy steels, that they should not be heated too quickly, and should be heated uniformly and as symmetrically as possible. In quenching care should also be taken that the material is cooled uniformly. In this way the internal stressing of the material is reduced to a minimum.

Hardened steel provides a very interesting study, since in that condition the steel is in a metastable state. It is of interest to record that so much is this the case that after quenching a hardened piece of steel will change dimensions, sometimes for many days after the hardening operation. Interesting experiments have been made which have clearly established [1] that there is a slight evolution of heat taking place at normal temperatures in the hardened mass.

[1] The Automobile Steel Research Committee's Report, 1920.

§ (44) Tempering.—Having once attained a satisfactorily hardened state in the steel, the tempering operation is then resorted to, to obtain exactly that condition of hardness and ductility which is required in the finished part. In cases where great hardness is required, tempering is not resorted to as in the case of some tools and some parts with wearing surfaces. It is known, however, that hardened steels, and particularly hardened alloy steels, may be tempered, with advantage, to low temperatures, 100°-300° C. (and in the case of high-speed steels to still higher temperatures), with the advantageous effect of removing, to a considerable extent, the internal stresses left in the material by hardening without impairing, sometimes indeed improving, the intrinsic hardness of the material.

Tempering, as generally applied to alloy steels, involves a uniform heating to 500°, 600°, 650° C., or whatever temperature is found necessary, maintenance at that temperature, and then cooling off either in water or in the air. Certain schools recommend quenching such alloy structural steels as nickel-chromium steels from the tempering temperature in water, since by this treatment a higher notched bar impact test value is obtained. Cooling off such steels in oil gives an intermediate result between the water-quenching and cooling in air.

In Tables 7 and 8 examples are given of the effect of hardening followed by tempering to various temperatures in the case of a carbon steel (6 H, Table 8) and in the case of a nickel steel (9 H, Table 7). Both steels

Table 7

Automobile Steel Research Report, 1920

9 H

Treatment.	Size of Bar.	Hardness. Brinell.	Tensile. Tons/Sq. In. Yield.	Tensile. Tons/Sq. In. M.S.	Tensile. Elongation per cent.	Tensile. Reduction per cent.	Impact. Izod Ft.-lbs.
Oil-hardened 820° C.; tempered 500° C.	$\frac{11}{16}$" diam.	331	66·0	72·0	19·0	58·0	30
	$1\frac{1}{8}$ "	331	65·0	71·0	19·0	56·0	28
	$2\frac{1}{8}$ "	331	64·5	71·0	17·0	52·0	26
	3 "	321	63·0	68·0	16·0	53·0	26
Oil-hardened 820° C.; tempered 600° C.	$\frac{11}{16}$ "	285	56·0	62·0	24·0	64·0	62
	$1\frac{1}{8}$ "	285	54·0	60·0	22·5	62·0	59
	$2\frac{1}{8}$ "	285	53 0	60·0	22·0	62·0	57
	3 "	285	55·0	60·0	22·0	60·0	60
Oil-hardened 820° C.; tempered 650° C.	$\frac{11}{16}$ "	269	50·0	58·0	25·0	66·0	77
	$1\frac{1}{8}$ "	269	48·0	57·0	24·0	65·0	74
	$2\frac{1}{8}$ "	262	48·0	56·0	25·0	67·0	74
	3 "	262	47·0	55·0	25·0	65·0	77

Table 8

6 H

Treatment.	Size of Bar.	Hardness. Brinell.	Tensile. Tons/Sq. In. Yield.	Tensile. Tons/Sq. In. M.S.	Tensile. Elongation per cent.	Tensile. Reduction per cent.	Impact. Izod Ft.-lbs.
Oil-quenched 870° C.	$\frac{11}{16}$" diam.	255	40·0	58·0	18·0	50·0	22
	$1\frac{1}{8}$ "	241	36·0	56·0	20·0	49·0	27
	$2\frac{1}{8}$ "	228	34·0	52·0	23·0	54·0	24
	3 "	217	32·0	49·0	23·0	55·0	26
Oil-quenched 870° C.; tempered 500° C.	$\frac{11}{16}$ "	255	39·0	56·0	21·0	57·0	40
	$1\frac{1}{8}$ "	248	36·0	55·0	21·0	54·0	32
	$2\frac{1}{8}$ "	228	34·0	52·0	23·0	54·0	31
	3 "	217	31·0	49·0	23·0	55·0	30
Oil-quenched 870° C.; tempered 600° C.	$\frac{11}{16}$ "	229	35·0	51·0	24·0	61·0	53
	$1\frac{1}{8}$ "	223	32·0	50·0	24·0	59·0	39
	$2\frac{1}{8}$ "	207	29·0	47·0	26·0	59·0	39
	3 "	202	27·0	45·0	26·0	59·0	39

have been treated in different thicknesses of section. The compositions were as follows:

	Carbon Steel.	Nickel Steel.
Carbon, per cent . .	0·45	0·31
Manganese, per cent .	0·78	0·70
Silicon, per cent . .	0·32	0·14
Sulphur, per cent . .	0·02	0·027
Phosphorus, per cent .	0·025	0·03
Chromium, per cent .	..	0·82
Nickel, per cent . .	..	3·27

The tests on these steels which are here quoted are part of an excellent and voluminous report upon steels used in automobile work.[1]

with a short round bar of wrought iron. If the wrought iron is heated to 900° to 1000° C. in intimate contact with a carbonaceous material it will be found that at the high temperatures carbide of iron, Fe_3C, is synthetically produced on the surface of the bar, and owing to the temperature this carbide diffuses inwards into the iron. It will thus be seen that a variable composition is given to the bar, *i.e.* the centre remains composed of soft iron crystals, the outside layers consist of pearlite (with perhaps a little cementite), whilst the intermediate layers are a varying mixture of iron crystals and pearlite. A reference to the iron-carbide diagram will make it clear that the outer layers become

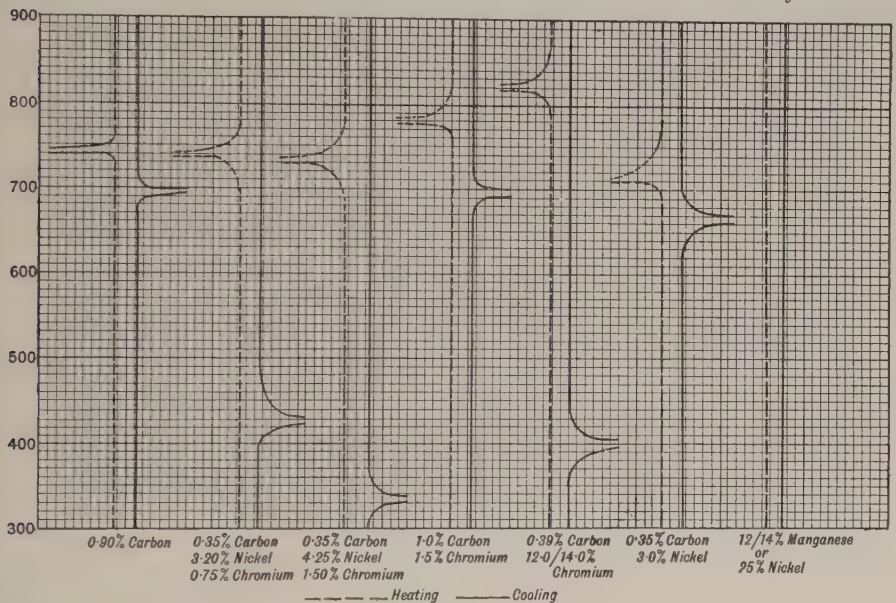


FIG. 3.

The research had the support of the whole of the engineering and metallurgical authorities of this country, and the report should be studied carefully by any one interested in alloy steels.

In *Fig.* 3 are given a few typical heating and cooling curves, which illustrate the effect which changes in composition have upon the critical points and emphasise the necessity for considering the heat-treatment of each steel on its own particular merits.

§ (45) CASE-HARDENING. — The process of case-hardening is based on the fact that by varying the carbon content in a single article the same heat treatment will produce dissimilar physical conditions. In the ordinary way, the process may be illustrated by an experiment

[1] The Automobile Steel Research Committee's Report, 1920.

solid solution on heating at so low a temperature as 730° to 740° C., whilst the centre does not undergo a transformation until 900° C. is reached. If, therefore, this particular bar be quenched from 760° C., the outer layers are intensely hard whilst the centre remains soft and ductile. This process has obtained wide use, particularly for the preparation of wearing surfaces and when a hard surface is required with a tough centre or back. Originally, wrought iron was used, but this was subsequently replaced by the more homogeneous low-carbon steel. It will, however, be appreciated that as the carbon of the steel employed is increased, so the difference in carbon content between the interior and the outer layers is decreased, and so greater accuracy in treatment and in a knowledge

of the process is required. Of late years alloy steels have been used for case-hardening purposes (see Table 14).

The addition of nickel raises the mechanical strength of the core without disproportionately reducing its ductility.

Chromium also has a similar effect, but the alloy steels usually employed are those of carbon content about 0·10 per cent with nickel either 2 per cent, 3 per cent, or 5 per cent. If the needs of the case warrant a nickel steel, the 5 per cent is the best to employ.

As regards the hard surface obtained with a nickel case-hardening steel, it should be recorded that it is very slightly less hard than a straight carbon steel.

IV. A Consideration of the Steels actually employed in the Industrial Arts

Under this heading it is proposed to discuss those actual steels which, as a result of experience, are at the present time utilised for different purposes. It naturally follows that the present industrial position as regards the use of steels is hardly in line with scientific knowledge to date, as there inevitably must be a considerable lag between the discovery of particular steels and their properties, and their actual use. This is particularly so as regards some of the new alloy steels; there are several which have now been thoroughly investigated and which have such intrinsic merits that they are worthy of much wider application, and it is hoped that this article may facilitate that development.

§ (46) Structural Steels. — Under this heading it is proposed to use the term "structural" in its broadest sense, including girders, angles, etc., which are usually known as structural steel; railway materials; large forgings; and automobile and aircraft steels, it being considered that such steels, whilst not representing all those which may be considered of the structural order, yet typify others not included.

(i.) *Mild Steels.*—As regards ordinary structural steels, viz. girders, angles, plates, etc., large quantities of cheap steel are needed, and the result is that, generally speaking, a mild carbon steel is employed. In Table 9 will be found the analyses and full mechanical tests of such material, together, for comparison's sake, with the analyses and mechanical properties of structural steel made during the war from shell discard, this being a ready way of using up a considerable amount of steel which otherwise would not have found an economic usage.

Structural steels are usually put into service simply in the rolled condition, but experience shows that the finishing temperature in rolling approximates to that of the normalising temperature, and hence the ultimate condition of the steel is reasonably satisfactory for the purpose for which it is intended. The microstructure of the mild steel consists of ferrite, strengthened up by a small proportion of pearlite.

(ii.) *Railway Steels.*—As regards railway materials, here again large quantities of material are required; and as it will be clear that changes in composition cannot be permitted in standardised parts without much deliberation, it is found that to-day practically the whole of the steels used for railway material are still the carbon steels. The carbon ranges from, say, 0·20 per cent in the mild-steel plates to 0·60–0·70 per cent in the harder tyres. In Table 10 will be found

Table 9

	Structural Steel (Ordinary).	Structural Steel (Shell Discard).
	per cent.	per cent.
Analyses—		
Carbon	0·20	0·60
Manganese	0·80	0·80
Silicon	0·12	0·12
Sulphur	0·05	0·05
Phosphorus	0·05	0·05
Mechanical tests—		
Tensile—		
Elastic limit, tons/sq. in.	12·2	18·7
Yield point, tons/sq. in.	15·8	32·2
Maximum stress, tons/sq. in.	30·8	54·9
Elongation	35·0	15·0
Reduction of area	61·0	29·3
Torsion—		
Yield, tons/sq. in.	11·3	17·5
Prob. max. shear stress, tons/sq. in.	25·5	37·3
Degrees twist	585	182
Impact—		
Izod impact, ft.-lbs.	35	5
Charpy impact, ft.-lbs.	19	4
Fremont, ft.-lbs.	51	..
Alternating stresses—		
Arnold reversals	369	300
Stanton blows	1230	1635
Sankey energy, ft.-lbs.	2700	1750
Hardness—		
Brinell No.	134	228
Shore No.	21	33

typical analyses, conditions, and mechanical properties of the essential items used on our railroads. Earlier in this article figures have been given showing the influence of a variable carbon content, and it is instructive to consider the use which has been made of this fact in connection with railway materials. For instance, take axles: here is an instance where, whilst considerable strength is required, yet owing to the necessity for resistance to fatigue a considerable capacity for plastic deformation is absolutely essential. It will, therefore, be seen that the railway engineer is content with a tensile strength in tons per square inch of 35-40 tons, accompanied by an elongation of 25-30 per cent and a reduction of area in the neighbourhood of 60 per cent. On the other hand, to consider railway tyres: what is there required is the resistance to wear combined with a sufficient strength, whereas, as shown by actual service conditions over a long period, ductility takes a secondary place, although it must be of a sufficient order to ensure absence of undue brittleness. Typical figures are given of three types of tyre which will enable a comparison to be made between the tyre material and the softer types before mentioned. Again, take rails: if too low a carbon material were employed, the wear would be excessive, and, therefore, it will be found that the railways have adopted a carbon steel of a mechanical strength of something like 45-50 tons per square inch in tension. Such material gives very considerably better results than the softer material, particularly the wrought-iron rails used a few decades ago. Another instance of high-carbon material used for railway purposes is the instance of the spring. For a successful spring a high elastic range and considerable strength are required, and this is obtained by taking a 0·50–0·60 per cent carbon steel and hardening and tempering it to the required degree. It is of interest to record that in a hardened and tempered spring there is very little free ferrite present.

Whilst discussing railway materials the author cannot do better than quote from an address recently given[1] by Sir Henry Fowler:

"Railway material offers very considerable difficulty in the collection of data as to the serviceability of material tested and passed for use, owing to the very long life of some of the principal parts.

"A very thorough method of testing is, however, of course absolutely necessary, as the failure of material on a railway may have very disastrous results, and it is therefore absolute 'safety first' that must be aimed at. Of the life which certain parts actually give, that of the straight axle may be taken as an example, and, while in some cases axles fail owing to repetition stresses, it often happens that an axle may give 300 to 400 million revolutions before being withdrawn either for wear or through a defect developing. The same thing holds good with regard to crank axles. A life of half a million to nearly one million miles is nothing exceptional, during which time the crank has been subjected to complicated repetition stresses during each revolution, apart from the shock arising at junctions, etc."

(iii.) *Large Forgings.*—The development of large power plants, both land and marine, together with the necessary transmission units, has resulted in a call for very large forgings—so large, indeed, that it is no uncommon thing in the Sheffield works to find ingots of 50-100 tons being manufactured for the purpose of producing one part. The steels most largely used for this purpose for shafts of one kind or another, turbine discs, etc., are carbon steels containing carbons ranging from 0·25–0·45 per cent. As typical of the actual analyses and mechanical properties associated with such forgings the writer cannot do better than quote the results obtained in a joint investigation conducted by Mr. Duncan and himself into the properties of turbine steels. In Table 11 will be found the analyses and mechanical properties of two turbine discs and two shafts in the actual condition in which they went into service. Such tests are typical of the material at present employed for such purposes. In Table 12 will be found the analysis and mechanical properties of a turbine disc which failed in service, and also of a rotor shaft which failed in service; whilst side by side will be found the mechanical properties of a shaft-end which, although only lightly stressed, was in service for eleven years before being taken out. Reference[2] to the original research should, however, be made for the full particulars, and also for the details of an interesting discussion which followed the reading of the paper. One interesting feature of the low-carbon steels such as those under consideration is that they are not readily seriously damaged in reheating unless heated to very high temperatures; and an interesting set of experiments, carried out by Mr. Duncan and the writer, are reproduced in Table 13 which should be studied carefully. The analysis of the material in this case was:

	Per cent.		Per cent.
Carbon	0·36	Phosphorus	0·032
Manganese	0·64	Nickel	0·08
Silicon	0·18	Chromium	0·08
Sulphur	0·044		

[1] Sheffield Association of Metallurgists, Sept. 1920.

[2] W. H. Hatfield and H. M. Duncan, "Turbine Steels, a Research into their Mechanical Properties," *North-East Coast Institution Engrs. and Shipbuilders*, March 19, 1920.

TABLE 10

RAILWAY MATERIALS

	Carbon Steel Axle.	Tyres.			Rail.	Springs.	Crank-Axle.	Ni-Cr Connecting Rod.	Mild Steel Plates.
		B.	C.	D.					
Analysis—									
Carbon, per cent	0·36	0·45	0·53	0·66	0·45	0·60	0·32	0·30	0·20
Manganese, per cent	0·81	0·82	0·87	0·76	0·80	0·75	0·75	0·61	0·80
Silicon, per cent	0·112	0·32	0·39	0·31	0·10	0·12	0·15	0·13	0·12
Sulphur, per cent	0·035	0·026	0·023	0·028	0·06	0·035	0·034	0·031	0·048
Phosphorus, per cent	0·032	0·038	0·036	0·034	0·05	0·033	0·031	0·032	0·045
Nickel, per cent	..	..	..	..	..	..	..	3·40	..
Chromium, per cent	..	..	..	..	..	..	..	0·65	..
Condition.	Oil-Hardened.	As Rolled.	Normalised.	Normalised.	As Rolled.	Hardened and Tempered.	Normalised.	Hardened and Tempered.	As Rolled.
Tensile—									
Elastic limit, tons/sq. in.	22·10	24·0	26·0	27·0	..	..	19·8	35·1	12·2
Yield, tons/sq. in.	26·00	28·0	29·5	32·4	23·1	63·0	21·3	43·0	15·8
Maximum stress, tons/sq. in.	39·50	46·6	53·2	60·2	46·5	76·0	34·2	53·0	30·8
Elongation, per cent, in 2 in.	27·0	20·0	18·5	12·5	19·5	9·5	32·6	24·0	35·0
Reduction of area, per cent	51·0	39·0	33·5	24·0	23·0	15·0	59·3	57·0	61·0
Torsion—									
Yield, tons/sq. in	14·0	14·0	17·2	17·2	14·5	35·0	12·7	28·5	11·3
Maximum stress, tons/sq. in.	29·5	31·5	37·2	37·2	33·3	47·0	26·7	38·5	25·0
Degrees twist	350	320	320	250	210	190	388	356	585
Izod—									
Ft.-lbs. energy	25	10	6	5	5	10	17, 19	45	80
Sankey—									
Ft.-lbs. energy	2700	1620	1120	900	1020	1100	2600	2500	2630
Arnold—									
No. of bends	390	270	310	260	370	160	430	250	470
Hardness—									
Brinell No.	170	202	235	262	202	328	156	244	134
Shore No.	31	36	40	44	36	52	29	42	26

TABLE 11

	Turbine Discs.				Shafts.				
	R.L. 6018 A.		R.L. 6018 B.		R.L. 5894.		R.L. 6206.		
	Sample 1.	Sample 6.	Sample 1.	Sample 6.	Longitudinal.	Transverse.	Longitudinal.	Transverse.	Radial.
Carbon, per cent	0·374		0·370		0·28		0·37		
Manganese, per cent	0·670		0·596		0·51		0·74		
Silicon, per cent	0·108		0·154		0·12		0·11		
Sulphur, per cent.	0·035		0·041		0·032		0·030		
Phosphorus, per cent	0·052		0·049		0·035		0·026		
Chromium, per cent	..		..		..		..		
Nickel, per cent	..		..		0·19		0 34		
E.L., tons/sq. in.	8·08	8·66	13·74	5·12	11·8	8·0	14·00	12·81	12·41
Y.P., tons/sq. in.	16·35	13·0	16·05	13·39	13·7	10·8	16·94	16·35	17·14
M.S., tons/sq. in.	32·9	29·03	31·5	28·2	28·4	25·6	36·78	34·36	35·16
Elongation, per cent	28·0	32·0	28·5	33·0	33·5	22·5	27·0	18·0	23·5
Red. of area, per cent.	45·8	54·6	47·15	55·8	53·4	33·5	41·87	30·55	36·33
Shear stress at yield, tons/sq. in.	10·4	8·0	10·97	8·37	9·1	9·5	10·34	10·15	10·24
Appar. max. shear stress, tons/sq. in.	35·7	33·3	34·3	32·6	31·7	32·4	34·17	33·06	33·99
Prob. actual max. shear stress, tons/sq. in.	26·8	25·0	25·7	24·4	23·7	24·3	25·63	24·8	25·5
Degrees twist	540	702	490	760	508	533	308	294	354
Izod, ft.-lbs.	4, 5, 4	5, 5, 5	5, 5, 5	5, 5, 5	16, 20, 20·5	11·5, 15, 12·5	8, 15, 15	12, 7, 14	12, 12, 10·5
Charpy, ft.-lbs.	3·5	4·0	4·0	3·5	6·9	8·0	8·4	8·0	10·1
Fremont, kgm.	2·0	2·0	2·0	2·0	7·0	1·0	..	..	..
Fremont angle	6°	5°	5°	6°	..	..	..	..	..
Fremont, ft.-lbs.	..	..	..	..	52·5	7·23	..	..	..
Stanton blows	553	556	597	471	956	629	1142	659	781
Arnold reversals	230, 196	340, 294	314, 176	354, 398	366, 512	302, 296	386, 428	88, 150	170, 262
Sankey alterns.	11·3	25·0	9·1	15·0	..	..	21·2	6·9	6·3
Sankey, max. B.M.	58	51·5	54·75	51	38	17	56·0	56·6	55·4
Sankey, ft.-lbs. energy	985	1860	730	1160	2600	1290	1830	615	540
Bend	175°	180°	180°	180°	..	..	..	..	..
Brinell, imp. m./m. (1500 kgm. load)	3·7	3·95	3·75	4·0	3·8	4·1	3·55	3·6	3·6
Brinell, hardness No.	135	118	131	114	128	109	147	143	143
Shore, hardness No.	29	27	30	27	20/21	19/20	27	28	28

TABLE 12

	R.L. 5983. Turbine Disc which failed.					R.L. 6053. Shaft End successful in work 11 years.			R.L. 6121. Rotor Shaft failed after 3 years.		
	Disc.		Boss.								
	Tang.	Radial.	Tang.	Radial.	Axial.	Tang.	Long.	Radial.	Tang.	Long.	Radial.
Carbon, per cent			0·44				0·44			0·50	
Manganese, per cent			0·63				0·68			0·84	
Silicon, per cent			0·25				0·12			0·06	
Sulphur, per cent			0·041				0·023			0·027	
Phosphorus, per cent			0·037				0·038			0·049	
Chromium, per cent			..				Absent			Trace	
Nickel, per cent			3·06				,,			,,	
Tungsten, per cent			..				,,			..	
Vanadium, per cent			..				,,			..	
Titanium, per cent			..				,,			..	
E.L., tons/sq. in.	..	..	..	..	..	12·8	..	11·8	16·15	16·55	Too small
Y.P., tons/sq. in.	..	29·25	29·07	..	..	19·7	18·71	21·08	26·29	22·16	26·1
M.S., tons/sq. in.	..	44·30	43·42	..	31·37	39·0	39·16	40·94	39·0	40·65	42·2
Elongation, per cent	..	25·3	32·7 per cent on $\frac{3}{4}''$ ·420″ diam.	..	1·33	22	25	12	2·5	22·0	7·0
Red. of area, per cent.	..	53·0	50·66	..	3·3	29·07	37·74	21·4	2·5	39·17	10·58
Shear stress at yield, tons/sq. in.	..	..	..	..	..	11·9	12·3	12·3	13·97	13·97	13·5
Appar. max. shear stress, tons/sq. in.	..	..	..	..	..	37·2	37·8	38·5	36·7	38·55	39·6
Prob. actual max. shear stress, tons/sq. in.	..	..	..	..	..	27·9	28·4	28·9	27·52	28·91	29·7
Degrees twist	..	..	..	..	..	256	346	300	150	360	120
Izod, ft.-lbs.	..	15, 17, 17	..	27, 25	..	5, 6, $5\frac{1}{2}$	4, 4, $3\frac{1}{2}$	6, 5, 5	3, 6, 5	10, 8, $7\frac{1}{2}$	$5\frac{1}{2}$, $5\frac{1}{2}$
Charpy, ft.-lbs.	..	$16\frac{1}{2}$, 15	16·0	14, 2, 14	5	2·9	3·25	3·1	3·1	4·45	5·7
Fremont, kgm.	..	5	..	..	..	..	..	..	..	..	..
Fremont angle	..	16°	..	..	..	..	..	..	..	..	..
Stanton blows	..	..	..	..	..	525	586	..	748	547	..
Arnold reversals	..	..	..	..	..	252, 240	394, 358	202, 170	176, 116	380, 322	8·18
Sankey alternate	..	..	..	..	..	11·4	14·1	7·1	1·3	12·3	3·3
Sankey, max. B.M.	..	..	..	..	..	61·4	63·7	61·8	71·0	63·9	61·25
Sankey, ft.-lbs. energy	..	..	..	..	..	1100	1330	610	126	1230	310
Bend	..	43	..	..	..	..	..	..	..	..	..
Brinell, imp. m./m.	..	..	..	..	..	4·6	4·5	4·55	..	4·4	..
Brinell, hardness No.	..	202	183	..	..	170	179	174	..	187	..
Shore, hardness No.	..	..	..	..	..	..	..	..	34	33	35

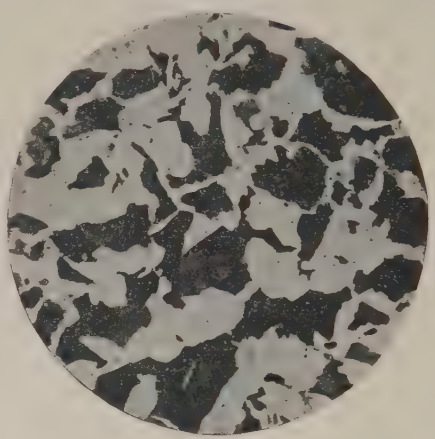
TABLE 13

R.L. 6311. Samples.	Treatment.	E.L.	Y.P.	M.S.	El. per cent.	R.A. per cent.	Izod. Ft.-lbs.	Stanton Blows.	Sankey.		Energy. Ft.-lbs.	Brinell No.
									Bends.	Max. B.M.		
1	850° C. for 2 hrs. and air-cooled .	..	21·1	34·4	34·0	56·9	38½, 30, 31	1341	30·2	60	2760	156
2	850° C. for 2 hrs. and slowly cooled	..	19·1	33·4	32·5	52·2	24, 24, 25	920	35·6	54·5	2840	144/146
3	950° C. for 2 hrs. and air-cooled .	16·7	19·9	37·4	27·0	47·1	32, 30, 29	1263	32·9	60·0	3020	151/160
4	950° C. for 2 hrs. and slowly cooled	15·8	16·9	33·9	31·0	47·1	20, 21, 20½	638 (faulty)	11·2	56·0	980	151
									18·4	57·5	1630	..
5	1050° C. for 2 hrs. and air-cooled	15·4	19·7	37·4	29·0	49·7	79, 31, 39 (piped)	1497	26·4	60·5	2420	151/160
6	1050° C. for 2 hrs. and slowly cooled	13·8	16·3	32·5	29·0	49·7	14, 15, 13	660 (faulty)	20·9	56·6	1830	146
7	1300° C. for 2 hrs. and air-cooled	17·7	20·0	37·3	24·0	36·3	15, 15, 19 (faint pipe)	1497 (faulty)	19·8	61·5	1900	151/160
8	1300° C. for 2 hrs. and slowly cooled	15·2	16·3	33·0	30·0	44·5	14, 13, 13	896	19·2	56·5	1680	134
9	900° C. for ½ hour air-cooled, followed by 600° C. for 5 hrs. and slowly cooled	19·7	20·5	34·3	32·0	56·9	29, 32, 32	1202	29·1	56·75	2500	134/160
10	900° C. for ½ hour air-cooled, followed by 680° C. for 5 hrs. and slowly cooled	16·94	18·12	31·55	39·0	62·57	32, 33, 36	640	34·9	54·1	2850	135
11	900° C. for ½ hour air-cooled, followed by 750° C. for 5 hrs. and slowly cooled	17·2	17·7	30·5	40·0	64·7	32½, 36, 41	690	30·4	55·1	2580	137

Slow coolings took approximately 7 hours down to 200° C. in 2, 4, 9, 10, and 11. In 8 no record taken.

One considerable difficulty in the past with regard to these carbon steels is that a common practice existed of close annealing, *i.e.* annealing such steels at temperatures just below the critical point, followed by slow cooling. Such practice is very unsatisfactory, since it results in the elastic range of the material being very materially lowered. Micrograph G reproduces the microstructure, at 100 diameters etched, of the shaft, full particulars of which are given in R.L. 6206, Table 11, and it will be seen that the structure consists of about equal amounts of ferrite crystals and of pearlite.

(iv.) *Auto and Aero Steels.*—Turning now to automobile and aero engineering. These branches may be considered the latest branches of engineering to be developed, hence practice as regards the use of materials was not stereotyped, with the result that far more use has been made of the special properties of alloy steels than in general engineering. The writer would therefore suggest that this section relative to automobile and aero engineering should be taken as being more important than even those branches of engineering would make it, owing to the practice as regards materials being representative of the most modern practice. Particularly does this apply to aero engineering where, during the war, the huge number of aero crankshafts manufactured consisted almost entirely of a nickel-chromium steel having a tensile strength of 60-65 tons per square inch. As regards the use of steel for these purposes, the writer would suggest reference to his paper given before the Institution of Automobile Engineers,[1] but the matter can be briefly summarised in the following manner. The steels available, apart from the carbon steels described in Table 1, are the two case-hardening steels and the nickel-chromium air-hardening steel described in Table 14, together with the 3 per cent nickel steel, 3 per cent nickel-chromium steel, chromium-vanadium steel, and 12-14 per cent chromium steel quoted in Table 15. In these tables will be found a detailed statement of the compositions, treatment, and mechanical properties of these several steels in the condition in which they are employed. Since it is easy to deduce from the name of a part the stresses and service which it is called upon to perform and thus enable comparisons to be made in other fields, it is proposed to state here, in some detail, the different parts in aero and automobile engineering which are made in these steels.



Micrograph G.—Carbon Steel Shaft. Etched. ×100.

For instance, take the 3 per cent nickel-chromium steel (Table 15) – 60-65 ton condition with a high elastic range of 45-50 tons accompanied by an elongation in the neighbourhood of 20 per cent; this steel has been found to serve admirably in the case of aero crankshafts, connecting rods, automobile connecting rods, crankshafts, clutch shafts, etc.

The 3 per cent nickel steel (see Table 15) in the hardened and tempered condition, having a tensile strength in tons per sq. inch of about 50, with an elongation approximating to 25 per cent, has been found to serve admirably for rear axles, front axles, torque tubes, steering columns, connecting-rod bolts, and in heavier vehicles for crankshafts, connecting rods, etc.

The chromium-vanadium steel (see Table 15) is also a satisfactory steel for most of the foregoing parts.

The air-hardening nickel-chromium steel (see Table 14) in the 100-ton condition has proved very useful for transmission gears, steering pinions, steering worms, and parts requiring great strength as well as resistance to wear, whilst in some aircraft this steel, in the air-hardened 100-ton condition, has been used successfully for connecting rods.

As regards the nickel case-hardening steel, this is used to a considerable extent in these fields; for instance, cams, camshafts, tappets, gear-box shaft, transmission work, valve rockers, gudgeon pins, and a number of similar parts are made successfully in this material.

The thing to be borne in mind is that with the introduction of the alloy steels the parts may be designed for the same weight with a greater elastic range, and thus that slight plastic deformation which inevitably takes place with a reversal of stress on the elastic range being slightly exceeded, is prevented.

[1] "The Most Suitable Steels for Automobile Parts," April 1920.

TABLE 14

	0·10 per cent Case-hardening Carbon Steel.	5 per cent Ni Case-hardening Steel.	Air-hardening NiCr Steel.	
			60-ton.	100-ton.
Carbon, per cent	0·11	0·14	0·30	
Manganese, per cent	0·73	0·29	0·40	
Silicon, per cent	0·10	0·16	0·105	
Sulphur, per cent	0·018	0·018	0·027	
Phosphorus, per cent	0·02	0·009	0·033	
Chromium, per cent	Nil	Nil	1·38	
Nickel, per cent	0·12	4·84	4·07	

Condition.	Normalised 900° C.	Normalised 900° C. Water Quenched 700° C.	Normalised 900° C. Water Quenched 760° C.	Normalised 900° C. Water Quenched 820° C.	Normalised 860° C.	Normalised 860° C. Water Quenched from 760° C.	Oil Quenched 830° C. Tempered 620° C.	Air Hardened 820° C.
Tensile—								
Elastic limit, tons/sq. in.	14·2	17·4	12·0	11·1	23·1	..	30·08	..
Yield point, tons/sq. in.	16·6	19·1	17·0	18·2	24·7	41·9	46·92	90·5
Maximum stress, tons/sq. in.	26·3	28·1	30·1	31·3	34·8	60·58	59·95	109·6
Elongation, per cent	37·0	38·0	33·0	32·0	31·0	17·5	21·0	9·0
Red. of area, per cent	61·8	68·8	63·3	62·1	62·1	46·9	53·8	21·0
Torsion—								
Yield	11·1	11·9	9·9	9·9	16·8	21·23	32·8	55·8
Probable maximum stress	22·8	24·8	25·9	27·2	26 0	41·85	39·2	67·26
Degrees twist	913	971	1028	1050	538	256	399	67
Izod, ft.-lbs.	83	93	90	80	85	23	45	15
Arnold reversals	269	293	355	250	360	190	205	146
Stanton blows	1242	1250	1236	1419	1284	10,112	7188	4380
Sankey, ft.-lbs.	1673	2976	1720	2333	5307	1,443	3102	573
Brinell hardness number	116	125	146	143	156	286	269	477
Shore hardness number	20	22	25	24	25	43	44	69

TABLE 15

	3 per cent Ni Steel.	3 per cent NiCr Steel.			Chromium-vanadium Steel.	12-14 per cent Cr Steel.	
						50-ton.	100-ton.
Carbon, per cent	0·39	0·32			0·46	0·28	
Manganese, per cent	0·55	0·60			0·64	0·22	
Silicon, per cent	0·110	0·12			0·19	0·102	
Sulphur, per cent	0·039	0·03			0·028	0·03	
Phosphorus, per cent	0·031	0·03			0·031	0·026	
Chromium, per cent	Nil	0·76			1·48	12·58	
Nickel, per cent	2·96	3·41			0·19	0·20	
Vanadium, per cent	..	..			0·33	..	
Condition.	Normalised 810° C.	Oil Quenched 850° C. Water Quenched 620° C.	Oil Quenched 850° C. Water Quenched 530° C.	Oil Quenched 850° C. Water Quenched 600° C.	Oil Quenched 850° C. Water Quenched 650° C.	Oil Quenched 850° C. Air Cooled 650° C.	Oil Quenched 950° C. Water Quenched 650° C.	Oil Quenched 950° C. Tempered 250° C.
Tensile—								
Elastic limit, tons/sq. in.	23·6	30·8	57·0	47·0	40·9	38·6	30·0	..
Yield point, tons/sq. in.	29·9	41·7	66·0	56·0	49·4	48·6	39·8	95·0
Maximum stress, tons/sq. in.	49·6	49·51	73·1	62·0	56·3	56·5	49·02	106·7
Elongation, per cent	22·0	24·0	18·0	21·0	24·0	22·0	22·0	7·0
Red. of area, per cent	47·0	63·6	56·0	62·0	66·0	60·4	55·0	29·5
Torsion—								
Yield	20·5	28·5	39·0	37·2	32·5	36·8	26·07	50·3
Probable maximum stress	34·5	34·5	43·0	39·6	36·5	39·0	32·9	57·4
Degrees twist	345	468	310	440	600	532	478	69
Izod, ft.-lbs.	19	72	26	49	65	35	48	8
Arnold reversals	250	250	230	240	260	280	168	152
Stanton blows	3100	4609	10,100	7700	3800	6264	4281	1651
Sankey, ft.-lbs.	2990	3100	2,600	3000	3100	4360	1440	1240
Brinell hardness number	228	228	321	277	248	255	217	444
Shore hardness number	35	35	50	45	38	41	35	64

As an instance of the relative behaviour of some of these steels under the Wohler fatigue test the following figures are quoted (Table 16). The data are derived from an extensive investigation which the writer is at present conducting at the Brown-Firth Research Laboratories relative to the fatigue range of the various kinds of steel when in the different conditions induced by heat-treatment.

Table 16

	·31 per cent Carbon Steel.	·60 per cent Carbon Steel.	3 per cent Nickel Heat-treated Steel.
Tensile—			
Elastic limit, tons/sq. in.	20·05	27·0	30·8
Yield point, tons/sq. in.	20·70	29·16	41·7
Max. stress, tons/sq. in.	35·17	48·6	49·51
Elongation, per cent	30·5	22·0	24·0
Red. of area, per cent	54·6	37·9	63·6
Wohler—			
Revs. ±23 tons	26,000	497,000	1,450,600
„ ±21 tons	100,300	600,500	10,000,000 *
„ ±19 tons	301,000	804,000	..
„ ±15·3 tons	1,720,000	..	..
„ ±13·5 tons	3,247,000	..	..
„ ±11·7 tons	10,000,000 *	..	..

* Unbroken.

The writer feels that, with a due appreciation by engineers of the properties of modern steels, considerable improvements in design may be achieved, and he looks forward to a very much larger use of alloy steels. Particularly is this so as regards the heavier units where mass makes it impossible, without additional alloys, to obtain anything but a relatively indifferent mechanical condition.

§ (47) Tool Steels, etc. (i.) *High Carbon Steels.*—The steels first used for tool steels were those containing high carbon contents, the carbon percentage ranging from 0·70 to 1·50 per cent. Such steels, in the soft condition, consist with the lower carbons almost entirely of pearlite and with the higher carbons of pearlite and cementite (or massive carbide of iron). As hardness was the essential property required, such steels were very satisfactory since they readily hardened at the relatively low temperatures of 750-800° C. They further readily tempered on heating to any required degree of hardness. It will therefore be seen that such material lent itself successfully to the production of a considerable number of tools, such as, for instance, turning, planing, and shaping tools, wood-cutting tools, saws of one kind or another, axes, paper and tobacco knives, cutlery, etc. Within the range of carbon mentioned all the requisite properties could be obtained. To take two extremes, an ordinary table knife could be made successfully from a carbon steel containing 0·70-0·90 per cent carbon, whilst a razor or a saw file might be made most successfully from carbon steel with a carbon content of 1·4-1·5 per cent.

On quenching the tool for the purpose of hardening from a temperature lying between 750° and 800° C. the material becomes converted into martensite, which is the product resulting from the quenching of the solid solution formed above the critical point. With carbon content much above 0·9 per cent some of the free carbide of iron which existed as cementite is distributed amongst this martensite as islands of carbide. Therefore, as the free carbide of iron itself retains, to a considerable extent, its intrinsic strength and hardness with some increase of temperature, whereas with arduous work the increase in temperature is sufficient to further temper the martensitic background in which the cementite carbide occurs, it will be appreciated that in the higher carbon tool steels the higher carbon is useful to the extent to which the hardness and cutting effect of the tool are reinforced by this free carbide. In Table 17 will be found a few particulars of some of these tool and cutlery steels.

Attempts were made from the beginning of last century to improve the cutting properties of tool steels by adding one or more of the different special elements, and success was achieved to a considerable extent. For instance, Mushet, by adding elements such as tungsten and chromium, produced what was known as a "self-hard" steel, *i.e.* the addition of the elements rendered more sluggish the change from the solid solution to the soft condition, and thus permitted more effective hardening and also produced a physical condition of the final steel which made it possible for the tool to stand up to its work much better than in the case of similar tools made of carbon steel.

TABLE 17

CARBON TOOL AND CUTLERY STEELS

	Carbon per cent.	Manganese per cent.	Silicon per cent.	Sulphur per cent.	Phosphorus per cent.	Brinell Number.
Razor . . .	1·4/1·5	0·22	0·12	0·03	0·01	600/650
Chisel . . .	0·85	0·25	0·15	0·03	0·01	..
Turning tool . .	1·25	0·25	0·15	0·03	0·01	..
Table knife . .	0·80/0·90	0·05	0·07	0·01	0·01	500/550
Pocket knife . .	0·80/1·0	0·22	0·12	0·03	0·01	550/600

(ii.) *High-speed Steels.*—The great development, however, came when the high-speed steels were discovered. With the development of engineering practice as regards machining operations it became a great advantage to have a tool that would do heavier work with less attention than heretofore. Take, for instance, a carbon tool steel turning tool. It will be appreciated that if the cutting conditions under which such tools are working become severe, considerable heat is generated, which has the effect of over-softening the nose of the tool and making it unfit for its work. It will therefore be clear that there was a limiting set of conditions under which carbon steel tools could operate.

With the addition of much tungsten and chromium it was found that if the steel was hardened from temperatures approaching the melting-point of the material a solid solution condition of the final tool was obtained which had very important properties, particularly as regards the maintenance of hardness with increasing temperatures. The result is that tools are so made that they will continue to cut when the tool is perceptibly red owing to the heat produced in the work done. There are now many high-speed tool steels which vary considerably in composition; the standard and widest known ones contain respectively about 14 and about 18/20 per cent of tungsten together with 3 or 4 per cent of chromium. Others contain substantial additions of vanadium, molybdenum, cobalt, and, indeed, so diverse are the compositions that those interested should refer to papers dealing with the subject. In Table 18 will be found a few typical analyses of various high-speed steels. It will be appreciated that owing to the addition of so much of the special elements the value of these steels is considerably increased, and as commercial products they are expensive and merit a careful understanding and treatment.

The forging temperatures of tool steels vary considerably; for instance, the temperatures at which to forge a tool in carbon tool steel range from 950° to 1050° C., and the higher temperature must not be much exceeded, since owing to the high carbon content the liquidus is widely separated from the solidus, and dangerous burning, with damage to the steel, may readily take place.

With regard to high-speed steel it may be pointed out that, generally speaking, forging may be done at substantially higher temperatures, and since the material cannot be burned except with temperatures well above 1300° C. the material may be forged with best advantage within the range 1050-1250° C. As regards annealing for the purposes of softening, this is done in the case of carbon steels by heating to a temperature of about 800° C. followed by slow cooling, *i.e.* the critical points are exceeded and advantage taken of the soft and pearlitic condition attained as a result of passing slowly through the critical range. With high-speed steel a temperature of about 750-800° C. is employed, which temperature range is below the carbon change-point, and hence advantage is really being taken of the tempering effect; in this case the steel may be cooled in air since the carbon change-point has not to be passed. In dealing with high-speed tools, particularly of complicated design, it is very important that in heating for hardening the tools should be warmed up gradually and not rapidly heated, as otherwise unequal stressing takes place and rupture may occur. To put high-speed steel into its best condition for purposes of tools it should be heated to just below its fusion point and either cooled in air blast or in oil. A low tempering temperature may be employed for the purpose of reducing the internal stresses left by such treatment, since such materials are not softened by tempering until temperatures in the neighbourhood of 600° C. are attained.

TABLE 18

TYPICAL HIGH-SPEED STEEL COMPOSITION

	(1).	(2).	(3).	(4).
Carbon . .	0·70	0·65	0·65	0·66
Tungsten . .	12·2	14·5	20·0	16·0
Chromium .	4·3	4·1	4·0	3·5
Vanadium .	Nil	1·0	1·5	1·0
Molybdenum .	Nil	Nil	Nil	2·0
Cobalt . . .	Nil	Nil	Nil	6·0

In Micrograph H will be found the microstructure of the carbon tool steel in the soft condition, showing a ground mass of pearlite through which are distributed membranes of carbide of iron. In Micrograph I will be found the microstructure of the same steel after quenching from 780° C., when it will be seen that the ground mass of pearlite has become changed into martensite. In Micrograph J will be found the structure of a high-speed steel in the soft condition, whilst in Micrograph K the structure is illustrated after hardening in the manner described, as a result of which process it will be found that the hardening has had the effect of preserving the solid solution condition of the material.

(iii.) *Cutlery Steels.*—Space does not permit the cutlery steels being much discussed, but the analyses will be found in Table 17. The essential point with regard to cutlery is that the knives shall have been properly hardened and suitably tempered to give the required hardness. Typical Brinell hardness figures for knives of various kinds will be found in the same table.

(iv.) *Spring Steels.*—With regard to spring steels, the properties and composition of a typical railway spring have already been stated. The major portion of the heavier springs manufactured are of carbon steel, but with the advent of the alloy steels considerable improvements have been brought about. The result is that in the case of automobiles, etc., a much more satisfactory spring is obtained. For a satisfactory spring a high elastic range is necessary, and the capacity for plastic deformation only enters into the matter in so far as it is sufficient to eliminate undue brittleness. Spring plates are now produced from chromium-vanadium steel, chromium-silicon steel, silico-manganese steel, and, indeed, other alloy steels, and the results obtained are typified in Table 19.

As the principal feature is the high elastic range free from brittleness, it follows that after hardening the spring should just be tempered in such a way that the tempering operation removes the extreme brittleness and internal stresses set up by quenching and, at the same time, retains a sufficient hardness in the steel. If spring plates are made of carbon steel there is a considerable danger in over-tempering, with the result that a low elastic range is obtained. The presence of alloys enables tempering for the removal of internal stresses without an undue depreciation of the elastic range. In the table will be found typical analyses and treatments.

TABLE 19

SPRING STEELS

	Carbon Steel.	Silicon-manganese Steel.	Chromium-vanadium Steel.
Analysis—			
Carbon, per cent	0·96	0·49	0·46
Manganese, per cent	0·26	1·14	0·45
Silicon, per cent	0·19	1·80	0·18
Chromium, per cent	..	..	1·45
Vanadium, per cent	..	..	0·19
Treatment.	**Water Quenched and Tempered.**	**Oil Quenched and Tempered.**	**Oil Quenched and Tempered.**
Tensile—			
Yield-point, tons/sq. in.	67·4	86·9	89·5
Max. stress, tons/sq. in.	89·8	92·2	107·3
Elongation, per cent	9·0	12·5	8·5
Red. of area, per cent	23·0	37·1	24·2
Izod impact, ft.-lbs.	11	14	14
Stanton blows	610	7320	9940
Brinell hardness No.	402	418	444

§ (48) RUSTLESS STEELS.—It is of interest to be able to state that there are now alloy steels which will resist certain corrosive media. Elsewhere the subject of corrosion is fully stated, hence it is only necessary here to describe the steels and their properties.

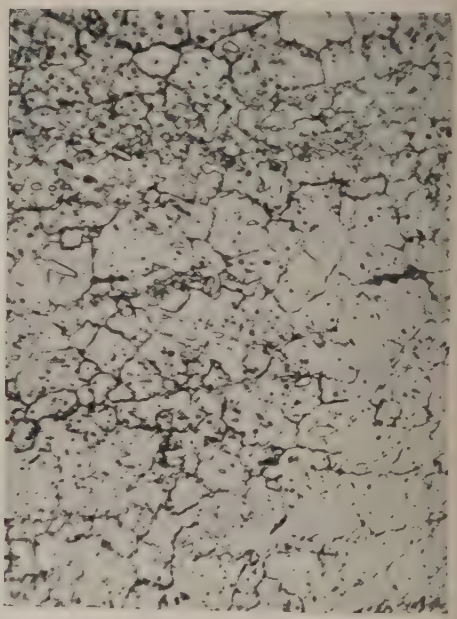
(i.) *Chromium Steels.*—It had long been known that alloys of iron and chromium were more resistant to ordinary corrosive influences than carbon steels and iron. This knowledge was gradually developed, but the real industrial achievement came when Brearley, some years ago, working in the Brown-Firth Research Laboratories, developed a chromium steel which could be hardened and tempered as a knife and yet possess such excellent non-corroding properties that the knives would successfully resist all the staining influences encountered in domestic use. This now well-known "stainless" steel was found to have other excellent properties, such as retention of strength to a marked degree with ascending temperatures, relatively good resistance to oxidation at higher temperatures, coupled with excellent mechanical properties at ordinary temperatures. Stainless steel may be well represented by the following analysis:

	Per cent.
Carbon	0·30
Manganese	0·30
Chromium	13·0

Micrograph H.—Annealed Carbon Tool Steel.
Etched. ×500.

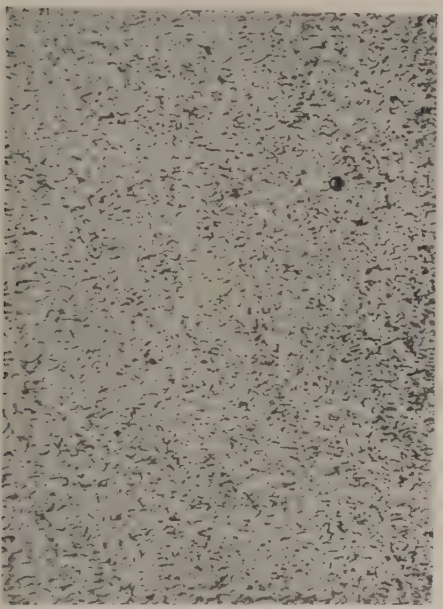
Micrograph I.—Hardened Carbon Tool Steel.
Etched. ×500.

Micrograph J.—Annealed High-speed Steel.
Etched. ×500.



Micrograph K.—Hardened High-speed Steel.
Etched. ×500.

The carbon change-point takes place at about 820° C., viz. nearly a hundred degrees higher than is the case in carbon steels. Experience proves the necessity of hardening by water or oil quenching from 950° C. to 1000° C. if after quenching a truly hard condition of steel is to be attained. Tempering by heating to gradually ascending temperatures softens the steel, and conditions may be obtained ranging from the properties of knife to those of a high tensile steel. In Micrographs L and M will be found respectively the microstructures of the annealed and hardened conditions.



Micrograph L.—Annealed Stainless Steel. Etched. ×500.

Micrograph M.—Hardened Stainless Steel. Etched. ×500.

In Tables 20 and 21 the range of conditions is illustrated.

In Table 22 fairly full mechanical properties are given for the two conditions in which it is likely to be of most service.

(ii.) *Stainless Steel.*—The stainless steel which is used for cutlery should be put carefully into the correct degree of hardness if the best stain-resisting condition is to be attained. There are many uses to which this stainless steel can be put, and indeed they are only limited by the supplies of the material. The steel may readily be forged hot to any particular shape that is required at temperatures round about 1150° C., and may subsequently readily be softened for machining purposes by annealing at a temperature of 750° C., *i.e.* since the carbon change-point in this steel is just over 800° C. this annealing really amounts to an over-tempering effect. Articles may subsequently be hardened and tempered after taking their final shape, allowance merely being made for finish grinding. In grinding such articles it is necessary to mention that the grinding operation itself is liable to lead to a scorching effect by over-heating, which will affect the stainless properties unless carefully prevented.

As an instance of the non-rusting properties of the material it may be mentioned that many knives have now been in use for a number of years in tropical countries, such as Equatorial Africa, Burma, and elsewhere, and have remained entirely bright and unstained.

It is of interest to record that this stainless steel has quite good properties as a permanent magnet, since with varying heat-treatments a coercive force of 46-69 may be obtained, together with a remanence of 7500-6040.

It is of interest to record that a further development of stainless steel has now been made by the original manufacturers, in that they are now able to produce a special stainless steel which has the particularly advantageous properties of being non-rusting and non-staining when in the soft condition. This now enables stainless steel articles to be manufactured in this newly developed steel by cold pressing, working, etc., without further treatment.

TABLE 20

OIL HARDENED 950° C., SLOW COOLED AFTER TEMPERING

Tempering Temperature. ° C.	Yield Point, Tons/Sq. In.	Max. Stress, Tons/Sq. In.	Elongation per cent.	Reduction of Area per cent.	Impact, Ft.-lbs.	Brinell.	
						Imp.	No.
100	95	120	4	12	5	2·65	532
300	90	100	8	20	8	2·90	440
500	83	89	10	39	..	3·05	402
550	64	68	12	47	13	3·55	293
600	42	49	23	60	..	4·0	228
650	42	49	22	57	44	4·0	228
700	..	..	..	..	72	4·25	202

TABLE 21

OIL HARDENED 950° C., WATER QUENCHED AFTER TEMPERING

Tempering Temperature. ° C.	Yield Point, Tons/Sq. In.	Max. Stress, Tons/Sq. In.	Elongation per cent.	Reduction of Area per cent.	Impact, Ft.-lbs.	Brinell.	
						Imp.	No.
100	95	120	4	12	5	2·65	532
300	90	100	8	20	8	2·90	440
500	81	84	7	39	7	3·0	418
550	61	66	16	52	15	3·50	302
600	45	50	21	59	19	3·8	255
650	43	49	22	59	54	4·0	228
700	36	44	26	66	86	4·3	196

TABLE 22

Condition.	Oil Quenched 950° C.	
	Water Quenched 650° C.	Tempered 250° C.
Tensile—		
Elastic limit, tons/sq. in.	30·0	..
Yield point, tons/sq. in.	39·8	95·0
Max. stress, tons/sq. in.	49·02	106·7
Elongation, per cent .	22·0	7·0
Red. of area, per cent .	55·0	29·5
Torsion—		
Yield	26·07	50·3
Probable max. stress .	32·9	57·4
Degrees twist . . .	478	69
Izod, ft.-lbs.	48	8
Arnold reversals . . .	168	152
Stanton blows . . .	4281	1651
Sankey, ft.-lbs. . . .	1440	1240
Brinell hardness No. . .	217	444
Shore hardness No. . .	35	64

(iii.) *Nickel Steels.*—Certain of the higher percentage nickel steels resist rusting influences reasonably well, but not as satisfactorily as the chromium steels just described. The corrosion of nickel steels has been investigated by Friend, Bentley, and West.[1] They conclude that the amount of corrosion with ordinary fresh water, sea water, and acid liquors decreases as the percentage of nickel increases. Steels containing above 18 per cent of nickel may be regarded as being practically non-corrodible. Professor Howe[2] gives the following comparative figures for the corrodibility of four steels, taking wrought iron as the standard (see Table 23).

TABLE 23

	Weathered.	Fresh Water.	Sea Water.	Average.
26 per cent nickel .	30	32	32	31
3 per cent nickel .	67	80	83	77
Mild carbon steel .	103	94	114	103
Wrought iron (standard)	100	100	100	100

D. M. Buck[3] shows that the presence of copper in nickel steel assists its non-corroding properties. Guillaume[4] states that a steel containing 42 per cent nickel is less subject to oxidation than other steels. Further information on the non-rusting properties of

[1] *Jour. Iron and Steel Inst.*, May 1912, and *Jour. Iron and Steel Inst.*, 1913.

[2] Greenwood and Sexton, *Iron and Steel*, p. 225.

[3] *Amer. Iron and Steel Inst.*, May 1915.

[4] *Comptes Rendus*, cliii. 156.

nickel steels may be obtained from the following publications: *Proceedings of the Faraday Society*, April 1916, ii. 212-234; *Bureau of Standards Circular*, April 1916, No. 58.

(iv.) *Silicon Alloys.*—In the range of compositions which may reasonably be called steels, the addition of silicon is not particularly advantageous, but if the percentage of silicon is raised to 15 per cent an alloy is produced which, whilst being very brittle and having mechanical properties of the order of those of poor cast iron, yet well resists some of the mineral acids. This alloy is manufactured and sold under different names in the form of castings.

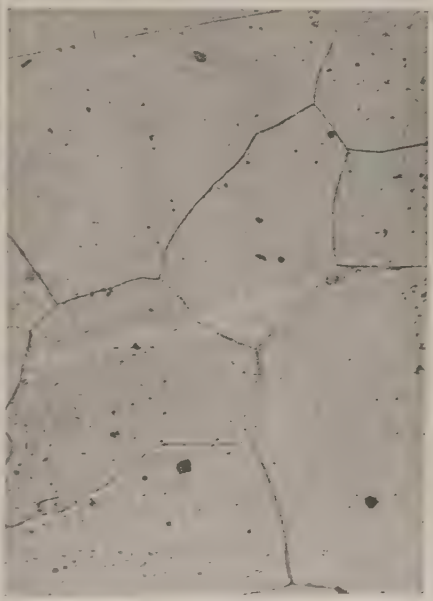
§ (49) Magnet Steels.—The steels which are used for the purpose of making permanent magnets are usually tungsten steels. They contain a carbon content of about 0·5-0·6 per cent, with usually a tungsten content of 5-6 per cent. To obtain the best properties as a magnet this material should be hardened from about 800° C. without any further tempering. Magnet steels are being manufactured, in lesser quantities, containing along with the tungsten a certain amount of chromium, whilst during the war chromium steels have been developed and, under the writer's own supervision, excellent results were obtained from simple ternary alloys of iron, carbon, and chromium. It may be said that a steel of a given composition will not necessarily give satisfactory results as a permanent magnet, since temperature influences upon the steel in process of manufacture have an important bearing. The microstructure of a magnet in good condition consists of martensite, with here and there traces of troostite, which fact indicates that the quenching operation for hardening should take place at a temperature not too high above the carbon change-point.

§ (50) Non-expanding Steel ("Invar").—Invar[1] contains about 36 per cent nickel with 0·5 per cent carbon and 0·5 per cent manganese. The coefficient of thermal expansion of this material between 0° and 200° C. is given as ·00000065 per ° C., or about $\frac{1}{15}$th that of steel. As commercially supplied it is usually rolled at a cherry-red heat and cooled in air. Guillaume states[2] that annealing at 900° C. slightly increases the coefficient of expansion, whilst quenching decreases it, the coefficient becoming negative and equal to −·00000053 per ° C. Cold-drawing has the same effect as quenching. Tempering cold-drawn wires at 250° C. for long periods increases the dilatability, the effect of quenching practically disappearing, whilst only 50 per cent of that due to cold work is removed.

§ (51) High Permeability Steels.—The ordinary steels manufactured for high permeability purposes are very low in carbon, a typical analysis being:

	Per cent.
Carbon	0·04
Manganese	0·21
Silicon	0·50
Sulphur and phosphorus	As low as possible

with no special elements present. It was found by Barrett, Brown, and Hadfield,[3] however, that the addition of increased quantities of silicon reduced the hysteresis losses, and there are therefore now on the market steels with carbon under 0·10 per cent. manganese 0·2-0·3 per cent, with silicon 3·0-4·0 per cent. The addition of silicon to the low carbon steel not only increases the permeability and hysteresis loss, but also increases the electrical resistance of the material considerably, this increase being of great advantage in reducing another source of loss of energy in transformers, *i.e.* the loss due to eddy currents.



Micrograph N.—Transformer Sheet. Etched. × 500.

The microstructure of a good transformer sheet is illustrated in Micrograph N. Such material is usually supplied in the form of

[1] See article "Invar and Elinvar."

[2] *Comptes Rendus*, 1916, clxiii. 654

[3] Barrett, Brown, and Hadfield, *Trans. Roy. Dublin Soc.*, 1899, vii. pt. 4, p. 116, and viii. pt. 1; Barrett, Brown, and Hadfield, *Jour. Inst. Elec. Eng.*, 1902, No. 156, xxxi. pt. 4, p. 708; Hadfield and Hopkinson, *Jour. Inst. Elec. Eng.*, 1911, xlvi. 235; Chubb and Spooner, *Elec. Jour.*, 1916, xiii. 393; T. Yensen, *Univ. of Ill. Eng. Exp. Stn. Bull.*, 1915, No. 83; T. Yensen, *Amer. Electrochem. Soc. Trans.*, 1917, xxxii. 165; A. Sanfourche, *Comptes Rendus*, 1918, clxvii. 683; Gumlich, *Elektrotechnik und Maschinenbau*, Sept. 1918.

sheets, but can be obtained in other forms, including that of castings of diverse shape.

Typical magnetisation curves for a few materials can be constructed from the following figures (Table 24):

TABLE 24

H. C.G.S. Units.	B. Lines per Sq. Cm. Wrought Iron. Annealed.	Ordinary Dynamo Sheet.	3½ per cent Silicon Steel Sheet.	Electrolytic Iron. Annealed.
1·5	8,000	4,150	9,350	13,500
3	11,100	9,400	11,750	14,800
5	12,800	12,150	13,050	15,250
10	14,600	14,700	13,950	15,750
20	15,650	15,820	14,500	16,150
30	16,300	16,100	14,860	16,500
50	16,900	16,700	15,550	17,600
100	17,950	17,750	16,850	19,250
200	19,250	19,100	18,250	19,650
400	20,800	20,650	19,450	21,000

The energy losses, using a maximum induction B of 10,000 C.G.S. at 60 cycles per second, with sheets of 0·35 mm. thickness, for ordinary steel are about 1 to 2 watts per lb. for hysteresis and 0·5 to 0·6 for eddy currents. The corresponding values for silicon steel are 0·5 to 0·8 and 0·12 to 0·18 respectively.

§ (52) NON-MAGNETIC STEELS. (i.) *Manganese Steel.*—Owing to the importance of this steel, which contains approximately 13 per cent of manganese, a separate article is devoted to it by the discoverer, Sir R. A. Hadfield.

(ii.) *Nickel Steels.*—Non-magnetic nickel steel, discovered by Professor Hopkinson[1] in the year 1889, has an average composition of 25 per cent nickel with 0·25 per cent carbon and 0·75 per cent manganese. When quenched from 550-600° C. this steel has a permeability of practically 1.

Colver-Glauert and Hilpert[2] give the following data (Table 25) concerning the magnetisability of 25 per cent nickel steel after various heat-treatments:

TABLE 25

Magnetising Force H.	4πI. Quenched from 600° C.	Quenched from 900° C.	Quenched from 1240° C.	Slowly Cooled from 1250° C.
15	0	6·2	152·5	18·22
25	0	20	315	32
50	0	25	630	85
75	0	30	843	112
100	0	35	989	140
150	0	52	1170	177
200	0	62	1337	213
300	0	68	1521	244

[1] *Proc. Royal Soc.*, 1890, xlviii.
[2] *Iron and Steel Inst.*, 1911, No. 1, 387.

The steel in the non-magnetic condition, when cooled below −40° C., becomes strongly magnetic, and this property is retained on returning to ordinary temperatures. The non-magnetic state may be reproduced by requenching from 600° C. The presence of chromium materially reduces the amount of nickel necessary for the production of a non-magnetic steel. A steel with a composition of 0·53 per cent carbon, 0·83 per cent manganese, 3·02 per cent chromium, and 16·05 per cent nickel is non-magnetic at ordinary temperatures. The references stated will be found useful.[3]

§ (53) ARMAMENT STEELS. —It may be said that the armament steels reflect to an efficient degree the progress of steel metallurgy. Unfortunately, the nature of the work prevents a full discussion. As a general statement it is true that where large masses are required the alloy steels which will best produce them are employed unhesitatingly, and it is hoped that the next decade will lead to the application of steels hitherto used almost solely for such purposes to general engineering uses. The nickel-chromium series of steels in particular has proved of great importance, and perhaps more research work has been done in connection with some of that series than in any other field.

APPENDIX

§ (54) CONDITIONS OF MECHANICAL TESTS QUOTED IN THE ARTICLE ON SPECIAL STEELS. (See *Fig.* 4.) (i.) *Tensile Test.* — Tensile tests are carried out in a 50,000 kgm. "Olsen" testing machine. This machine is of the multiple lever type. The machine is fitted with gear for automatically adjusting the jockey-weight forwards or backwards so as to keep the lever in balance.

The standard form of test-piece is 2″ parallel, ·564″ diameter, and over-all length 7″. The pull is applied through heads in the ends of the test-piece, 1½″ diameter. These are held in screw adapters which connect through the shackles of the machine by spherical-seated nuts. The standard rate of pulling adopted is ·31″ per minute. The yield-point of the material is taken as the stress which gives a permanent set of the test-piece of 1/100″. For ordinary tests this extension is determined by using dividers set to the gauge length.

[3] Barrett, Brown, and Hadfield, *Jour. Inst. Mech. Eng.*, April 1902, xxxi., and April 1911, xlvi.; Colver-Glauert and Hilpert, *Jour. Iron and Steel Inst.*, Sept. 1912; Hilpert and Mathesius, *Jour. Iron and Steel Inst.*, Sept. 1912; Burgess and Aston, *Met. and Chem. Engr.*, Jan. 8, 1910, 23-26; Honda and Takagi, *Tôhoku Univ. Sci. Reps.*, April 6, 1918, 321-340.

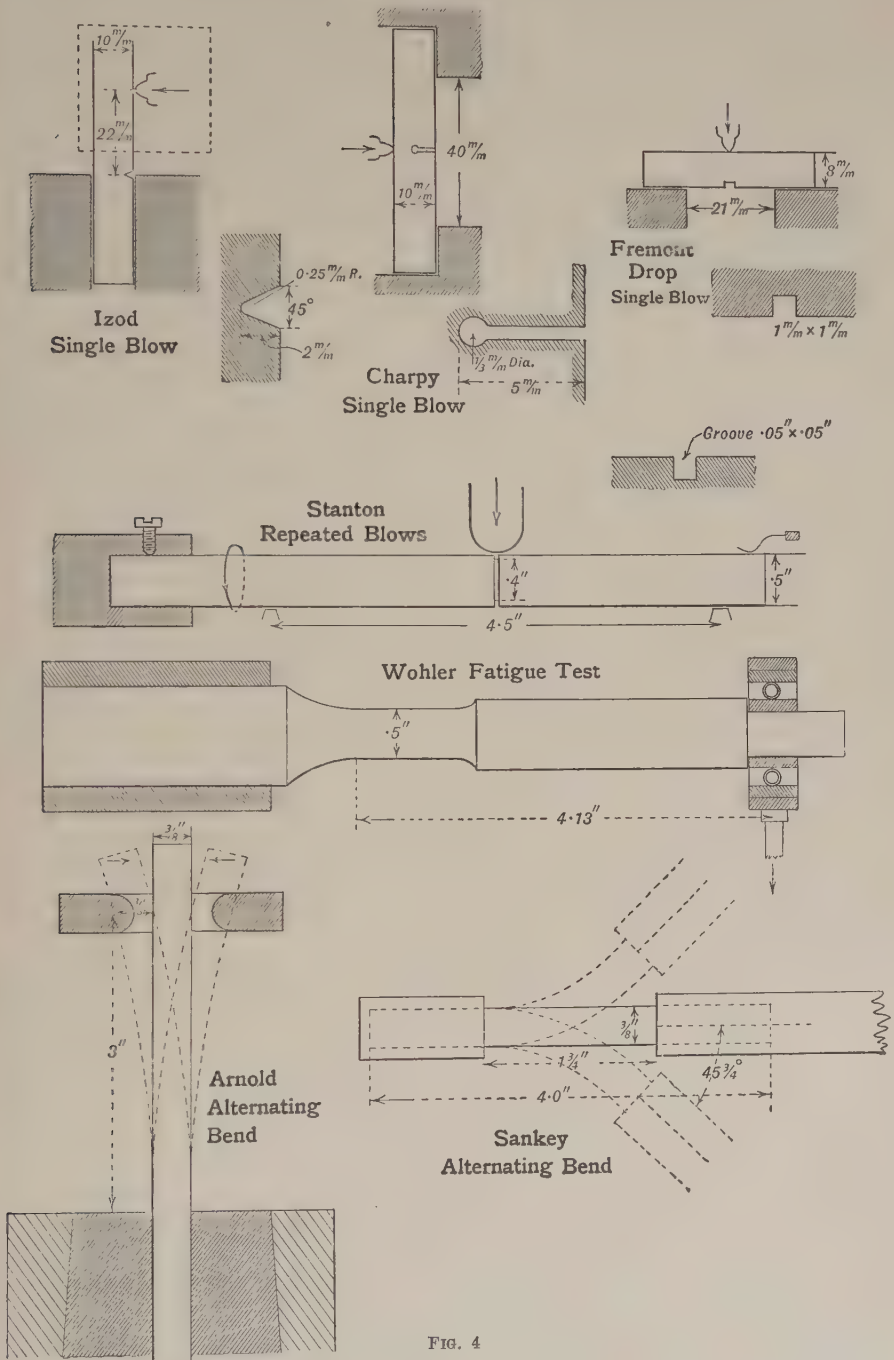

10 m/m
22 m/m
Izod
Single Blow
0·25 m/m R.
45°
2 m/m
40 m/m
10 m/m
Charpy
Single Blow
⅓ m/m Dia.
5 m/m
8 m/m
21 m/m
Fremont
Drop
Single Blow
1 m/m × 1 m/m
Groove ·05" × ·05"
Stanton
Repeated Blows
·4"
·5"
4·5"
Wohler Fatigue Test
·5"
4·13"
⅜"
3"
Arnold
Alternating
Bend
⅜"
1¾"
45 ¾°
4·0"
Sankey
Alternating Bend

FIG. 4

For special tests, including determinations of the elastic limit of the material, an extensometer of the "swing" type is fitted to the test-piece. In this instrument a small glass scale is given a movement equal to five times the extension of the test-piece across the objective of a microscope. By means of another scale in the eyepiece of the microscope the extension of the test-piece is easily measured in units of 1/12500″. For determination of the elastic limit, gradually increasing loads are applied to the piece and the extension for each load is observed. From the results a graph is plotted showing the relation between load and elongation.

The elastic limit of the material is taken as the limit of proportionality, which is indicated by the upper end of the straight line portion of the graph which is obtained. The yield-point, according to the previous definition of this quantity, may also be determined from such a graph.

(ii.) *Torsion Test.*—The torsion test consists of twisting to destruction of a suitably prepared test-piece and observing the torque or twisting moment required to do this and the amount of deformation produced in the test-piece.

The dimensions adopted for our tests are: overall length 5″, parallel portion $\frac{3}{8}$″ diameter, $1\frac{3}{4}$″ long, with heads 1″ square at the ends. The ends of the parallel portion are turned to $\frac{1}{2}$″ radius. The tests are carried out in a 10,000 in.-lbs. "Avery" Torsion Machine. In the first portion of the test the angle of twist is increased by increments of half a degree, and the twisting moment indicated by the machine for each angle is observed. From the readings a graph is prepared, connecting the angle of twist and the twisting moment, and from the limit of proportionality indicated by this graph the value of the twisting moment at elastic limit of the material is obtained. Observations are also made of the maximum twisting moment endured by the material and of the total angle of twist up to fracture of the test-piece. The values of twisting moment obtained for the elastic limit and for the maximum stress are converted into terms of shear stress by application of the usual formula for shear stress in twisted shafts, viz.:

$$\text{T.M.} = \frac{\eta}{16} D^3 fs,$$

where *fs* denotes the intensity of the shear stress at the skin of the material.

This formula only strictly applies to conditions within the elastic range.

The value of *fs* calculated from this formula by substituting the maximum value of the T.M. is referred to as the "apparent maximum shear stress" on the material.

It is recognised that this formula does not indicate the real maximum shear stress which the material can stand, and that a more likely value for this quantity is obtained by using the formula:

$$\text{T.M.} = \frac{\eta}{12} D^3 fs.$$

The value of *fs* obtained from this latter calculation is referred to as the "probable actual maximum shear stress."

(iii.) *Bend Test.*—A rectangular piece $\frac{3}{8}$″ × $\frac{3}{4}$″ section and about 8″ long is supported with the broadside horizontally on rollers 3″ diameter at $5\frac{1}{2}$″ span. A tool having a radius of $\frac{3}{4}$″ at the tip is pressed down vertically at the centre of the test-piece, and the downward deflection is continued until either fracture takes place or the legs of the piece have become parallel.

The angle of bend at which fracture takes place, if it does so, is noted.

(iv.) *Charpy Test.*—The test-piece, 10 mm. square, 60 mm. long, is supported horizontally, and the pressure from the pendulum is applied horizontally at its centre, pressing the piece against abutment at 40 mm. span. A "keyhole notch" 5 mm. deep is made in the test-piece at the middle of the span and turned away from the side receiving the blow. The diameter of the drill hole at the bottom of the notch is $1\frac{1}{2}$ mm.

The energy absorbed in fracturing the piece is measured by the reduction in the angle of swing of the pendulum in the same way as in the Izod machine.

The results may be expressed in foot-pounds or in kilogram-metres, or in kgm. per square centimetre of cross-section at the fracture. Wt. of tup, 22 5 kilos. Capacity of machine, 30 kgm.

(v.) *Fremont Test.*—The piece, 8 mm. × 10 mm. section and 30 mm. long, is supported horizontally on supports 21 mm. span. The notch is 1 mm. deep and 1 mm. wide, square shape, made on the broadside at the centre of the length.

The piece is fixed with the notch on the under side and receives a blow from the tup which has fallen through a height of several metres. The difference between the initial and residual energy of the tup is the amount absorbed in fracturing the piece. The striking velocity in this test is higher than that in the Izod or Charpy machine.

(vi.) *Izod Test.*—The test-piece, 10 mm. square in section, is notched transversely by a "V" cutter to a depth of 2 mm. and an angle of 45°. The radius at the bottom of the notch is $\frac{1}{4}$ mm. The piece is fixed vertically in the vice of the machine by the lower end, with the notch at the level of the face of the vice. The pendulum of the machine is released when it swings freely, and a knife edge carried in the tup of the machine strikes the piece at a distance 22 mm. above the notch, on the same side as the notch. The angle of swing of the pendulum beyond the vertical after breaking the test-piece is indicated by the pointer. From the amount by which the angle falls short of the angle to which the pendulum would have swung if there had been no test-piece, the amount of energy absorbed in breaking the test-piece is known, and is read by the pointer in ft.-lbs.

Three tests are usually done on one piece, the notches being placed on different sides of the piece. The height of fall of the centre of mass of the pendulum is $2\frac{1}{2}$ ft., and the capacity of the machine 150 ft.-lbs., or 120 ft.-lbs., the distance from the pivot to the striking edge being 4 ft. The striking velocity (when using the full capacity of the machine) is 13·6 ft.-sec.

(vii.) *Arnold Alternating Test.*—The piece, $\frac{3}{8}$″ diameter and 6″ long, is rigidly clamped in a vertical position in the vice of the machine.

A collar fits loosely over the top of the piece, at a height of 3″ above the face of the dies, and is given

a reciprocating motion, causing it to bend the piece alternately backwards and forwards through a distance of $\frac{3}{8}''$ on either side of the vertical. The standard speed adopted is 650 alternations per minute. The number of alternations to fracture is recorded.

(viii.) *Stanton Test.*—This is an alternating shock test. The test-piece is turned to $\frac{1}{2}''$ diameter and $6\frac{1}{2}''$ long. It is supported by supports $4\frac{1}{2}''$ span. The test-piece has a groove turned round the centre of the span ·05″ deep and ·05″ wide. The corners of the groove are practically square, the actual radius approximating to ·001″. This is fixed in the machine, where it receives blows from a hammer whose weight is 4·7 lbs. and of which the height of fall is adjustable. In the present tests the height of fall is kept at 2″. After each blow the machine rotates the test-piece through 180°. The frequency of the blows is kept fairly constant at 96 per minute. The test is allowed to proceed until the piece fractures at the groove, and the number of blows withstood before fracture is recorded by a counter on the machine. The machine itself has a fairly heavy bedplate and is allowed to rest on a concrete floor. This gives a fairly firm foundation to withstand the shock.

A complete description of this machine, which is called the "Stanton Repeated Blow Impact Machine" and is made by the Cambridge Scientific Instrument Company, may be found in this Company's catalogues, or in the *Journal of the Iron and Steel Institute*, Carnegie Number for 1914.

(ix.) *Sankey Test.*—This is carried out in a machine made by Messrs. Casella & Co., Ltd. The test-piece is $\frac{3}{8}''$ diameter and 4″ long. It is clamped at one end in a grip carried at one end of a stiff cantilever spring. At the other end of the piece a long handle is fixed, leaving a free length of test-piece of $1\frac{3}{4}''$. This is bent backwards and forwards through a standard angle, which is about $45\frac{3}{4}''$ on each side of the straight, until the piece breaks. The slight movement of the spring actuates a mechanism which records the value of bending moment put on to the piece at each reversal. From the autographic diagram, the amount of energy expended in fracture can be determined.

(x.) *Brinell Test.*—This consists of pressing a hard steel ball 10 mm. diameter into a flat surface of the material to be tested, with a standard pressure, and measuring the diameter of the permanent impression made.

The pressure is obtained by oil acting on a small piston and operated by a hand-pump. The standard test is made with a pressure of 3000 kg. kept steady for 30 seconds. With small samples, the steady pressure used may be made 1500 or 500 kg.

In each case the hardness value is given as the pressure per square millimetre of the concave surface of the impression. The conversions from millimetres diameter to hardness number are ready worked out in the form of a table.

(xi.) *Scleroscope Hardness Tests.*—These are made by means of the "Shore Scleroscope." The instrument consists of a glass tube about 10″ long in which slides a small steel hammer, having a diamond tip at the under side.

The material to be tested has one surface ground and polished to a finish corresponding to about "F" emery cloth.

The tube is placed vertically over the surface in contact with it, the piece being rigidly held. The hammer is released from the top of the tube, and a scale reading taken corresponding to the height of rebound represents the hardness of the material in "degrees Shore."

The instrument is checked for accuracy in reading by obtaining the values given by specially prepared blocks of standard hardness, supplied by the Shore Instrument Co.

(xii.) *Wohler Tests.*—The Wohler test is carried out by rotating the bar, fixed at one end and carrying a load at the other, in cantilever fashion. The portion of the test-piece which is most severely stressed is usually somewhat smaller in diameter than the rest of the bar, and this portion is terminated by gradually "radiused" portions, as indicated in the diagram on p. 557. The value of the stress acting in the material at the most severely stressed point is usually calculated according to the elastic theory, *i.e.*

$$\text{Max. Stress} = \frac{\text{B.M. at section}}{\text{Modulus of section}}.$$

At any instant the upper fibres of the test-piece carry the maximum tensile stress in the material and the lowest fibres carry the maximum compressive stress. During the rotation of the test-piece it is seen, therefore, that a particular point in the surface of the bar passes through a cycle of change of stress starting from maximum tension, changing gradually to maximum compression, and then changing back again to maximum tension.

In testing a particular material series of tests are made in which the test-piece is stressed to different intensities, the aim being to determine the value of stress under which the material could be run for an indefinite number of revolutions without fracture.

W. H. H.

STELLITE: a hard, non-ductile alloy used in the manufacture of cutting-tools. See "Alloys, Some Special," § (3).

STRIPPING MATERIALS IN COPPER REFINING. See "Copper, Electrolytic Refining of," § (9).

STRUCTURAL STEELS. See "Steels, Special," § (46).

SULPHUR, existence in steel. See "Iron-carbon Alloys," § (14); also "Steels, Special," § (36).

SULPHURIC ACID added to copper-plating bath. See "Copper, Electrolytic Refining of," § (3).

SURFACE COMBUSTION FURNACE. See "Furnaces for Laboratory Use," § (10).

— T —

Tantalum, physical properties of. See "Alloys, Some Special," § (4).
In steel. See "Steels, Special," § (25).

Temper Colours in steel. See "Iron-carbon Alloys," § (11).

Temperature, high, influence on physical properties of steels. See "Steels, Special," § (4) (B).
Low, influence on the physical properties of iron and steel. See *ibid.* § (4) (A).
Measurement of furnace. See "Metals, Thermal Study of," § (4).
Time curves. See *ibid.* § (8).
Uniformity of, in a furnace. See "Furnaces for Laboratory Use," § (1).

Tempering: modification of the hardness of a quenched or cold-worked metal (usually steel) by subsequent moderate heating, followed by cooling in air, oil, or water. See "Metals, Thermal and Mechanical Treatment of," § (11); also "Steels, Special," § (44).
Of steel. See "Iron-carbon Alloys," § (11).

Ternary Alloys. Soe "Metals and Alloys, Micro-structure of," § (8); also "Steels, Special," § (11) (ii.).

Ternary System in a series of alloys. See "Alloys, Constitution of," § (4).
Of alloys, different types of. See *ibid.* § (5).
Of alloys, representation by a solid model. See *ibid.* § (4) (ii.).

Thermal Conductivity of alloy steels. See "Steels, Special," § (10).
In relation to a composition of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (3).

Thermal Curves. See "Metals, Thermal Study of," § (8).

Thermal Electro-motive Force in relation to composition of alloys. See "Alloys, The Relationship of Structure and Physical Constants," § (4).

Thermal Study of Metals. See "Metals, Thermal Study of."

Thermal transformation points in iron. See "Iron-carbon Alloys," § (3).

Thermo-couples, for measurement of furnace temperatures. See "Metals, Thermal Study of," § (4); see also "Thermo-couples," Vol. I.

Three-phase Furnace. See "Furnaces, Electric," § (4) (iv.).

Tin in steel. See "Steels, Special," § (23).

Tin-phosphorus Alloys. See "Alloy Systems, Typical," § (12).

Tool Steels. Analysis; hardness. See "Steels, Special," § (47), Table 17.

Transformers, for electric furnace work. See "Furnaces, Electric," § (3) (iii.); see also "Transformers, Static," Vol. II.

Transparent Reflector: a disc of thin plain glass placed at an angle of 45° across the axis of a microscope directly opposite an aperture in the side of the tube, as used for the examination of metals under "normal" or "vertical" illumination. See "Metals, Microscopic Examination of," § (6).

Trilinear Co-ordinates in a ternary system of alloys. See "Alloys, Constitution of," § (4) (i.).

Troostite: a constituent of steel. See "Metals and Alloys, Micro-structure of," § (7); also "Iron-carbon Alloys," § (10).

Tube Furnaces. See "Furnaces for Laboratory Use," § (2).

Tubes. See "Metals, Thermal and Mechanical Treatment of," § (7).

Tungsten, physical properties of. See "Alloys, Some Special," § (4).
In steel. See "Steels, Special," § (32).

Tungsten Steel, effect of temperature on tensile strength. See "Steels, Special," § (4) (B) (i.), Table 4.
As magnets, coercive force 55/65, remanence 9/11,000. See *ibid.* § (9).

Twinned Crystals consist of two individuals united symmetrically about a plane, which is a possible face of the crystals of the substance, or about an axis which is a possible crystal edge. In metal sections twinning makes itself evident by the presence of bands of different but uniform orientation forming parallel systems. See "Metals, The Relations of Strain and Structure," § (1); see also "Crystallography," Vol. IV.

Type Metals: lead-antimony alloys, containing bismuth or tin, employed for type-founding. See "Alloys, Some Special," § (7).

— U —

Uranium in steels. See "Steels, Special," § (34).

— V —

VACUUM FLASKS, for maintaining cold junction of thermo-couples. See "Metals, Thermal Study of," § (4).

VACUUM FURNACE. See "Furnaces for Laboratory Use," § (6).

VANADIUM in steel. See "Steels, Spécial," § (24).

VERTICAL ILLUMINATION: the method of illuminating a specimen under microscopic examination so that the light falls upon the surface of the specimen in a direction at right angles to that surface. See "Metals, Microscopic Examination of," § (6).

— W —

WATCHES, compensation of, use of elinvar for. See "Invar and Elinvar," § (13).

WELDING: the property possessed by some metals of adhering when subjected to an external force, such as hammering. See "Metals, Defects and Failure of," § (6).

WIRE-DRAWING: the production of rod or wire of small diameter by forcibly pulling a rod through successively smaller holes in a plate or die. See "Metals, Thermal and Mechanical Treatment of," § (7).

WROUGHT ALUMINIUM ALLOYS. See "Aluminium Alloys," § (5).

WROUGHT IRON. See "Iron-carbon Alloys," § (4).

Analysis, strength, hardness, effect of low temperature. See "Steels, Special," § (4) (A) (i.).

Effect of temperature on tensile strength. See *ibid.* § (4) (B) (i.), Table 3.

— X —

X-RAY ANALYSIS applied to metals. See "Metals and Alloys, Micro-structure of," § (2); see also "Crystallography," § (15), Vol. IV.

— Z —

ZINC in steel. See "Steels, Special," § (16).

Furnaces for manufacture of. See "Furnaces, Electric," § (6).

ZIRCONIA, for furnace tubes: a rare earth oxide, used as the heating element in a furnace developed by Harker. See "Furnaces for Laboratory Use," § (2).

Properties of. See "Refractories," § (49).

ZIRCONIUM in steel. See "Steels, Special," § (19).

APPENDIX

MAGNETIC MEASUREMENTS

CLASSIFIED REFERENCES TO THE ARTICLE IN VOLUME II

A. *Standard Instruments and Apparatus*

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